U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-270 015

Evaluation of Exhaust Recirculation for NOx Control. Volume I, and Volume II Appendix

Esso Research and Engineering Co, Houston, Tex Products Res Div

Prepared for

National Air Pollution Control Administration, Ann Arbor, Mich

Jul 69

PB 270 015

FINAL REPORT

EVALUATION OF EXHAUST RECIRCULATION FOR NO_x CONTROL

Motor Vehicle Emission Lab
LIBRARY

Volume I

Contract No.: PH 86-67-25
National Air Pollution Control Administration
Department of Health, Education and Welfare

Esso Research & Engineering Company
Products Research Division
July 1, 1969

NATIONAL TECHNICAL
INFORMATION SERVICE

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

3. Recipient's Accession No.

4. Title and Subtitle
Evaluation of Exhaust Recirculation For NOx Control, Vol. 1

5. Report Date
July 1969

6.

7. Author(s)
Esso Research and Engineering Company

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Esso Research and Engineering Company
Products Research Division
Houston, Texas

10. Project/Task/Work Unit No.

11. Contract/Grant No.
PH 86-67-25

12. Sponsoring Organization Name and Address
National Air Pollution Control Administration
Department of Health, Education and Welfare
Ann Arbor, Michigan 48105

13. Type of Report & Period Covered
Final Report

14.

15. Supplementary Notes

16. Abstracts

The NAPCA-Esso study summarized in this report investigated: Feasibility of the recirculation technique when used in conjunction with positive crankcase ventilation and with the Engine Modification System with Manifold Air Injection; design characteristics needed for an automatic system to provide emission controls while retaining fuel economy and vehicle performance. The goal was to determine the desirability of carrying out further studies concerning long-term operability, effectiveness and engine wear effects of exhaust recycle in combination with hydrocarbon and CO control systems. The program was divided into two phases: a laboratory engine phase where four different engines were operated over a wide range of steady-state conditions and a vehicle test phase where two fully-equipped cars were studied under transient conditions.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Motor vehicles
Exhaust emissions
Nitric oxide
Exhaust systems

17b. Identifiers/Open-Ended Terms

Recirculation technique
Emission control technology
Positive crankcase ventilation

17c. COSATI Field/Group

18. Availability Statement
Release Unlimited

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages
306

22. Price
A14-A01

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

FINAL REPORT

EVALUATION OF EXHAUST RECIRCULATION FOR NO_x CONTROL

Volume I

Contract No.: PH 86-67-25
National Air Pollution Control Administration
Department of Health, Education and Welfare

Esso Research & Engineering Co.
Products Research Division
July 1, 1969

TABLE OF CONTENTS

Page

SUMMARY 1

1.0 INTRODUCTION 9

2.0 LABORATORY ENGINE PHASE 15

2.1 PROGRAM OUTLINE 15

2.1.1 Test Engines 15
2.1.2 Independent Variables 15
2.1.3 Dependent Variables 15
2.1.4 Selection of Speed-Load Conditions 15
2.1.5 Selection of Spark Timing 19
2.1.6 Selection of Air-Fuel Ratio 19
2.1.7 Selection of Recirculation Rate 20
2.1.8 Selection of the Recirculation Gas Temperature 20
2.1.9 Selection of Air Injection Rate 20

2.2 EXPERIMENTAL PROCEDURE 21

2.2.1 Break-In 21
2.2.2 Test Procedure 21
2.2.3 Recycle Flow Control 24
2.2.4 Instrumentation 28

2.2.4.1 Engine Speed and Load 28
2.2.4.2 Spark Timing 28
2.2.4.3 Engine Air Flow Rate 28
2.2.4.4 Engine Fuel Flow Rate 28
2.2.4.5 Exhaust Recirculation Rate 28
2.2.4.6 Exhaust Gas Analysis 29

2.3 MATHEMATICAL ANALYSIS OF ENGINE-TEST DATA 31

2.3.1 Reduction of Raw Data 31
2.3.2 Choice of Air/Fuel Ratio Calculation 31
2.3.3 Choice of Percent Recycle Calculation 34
2.3.4 Data Correlation by Regression Analysis 35
2.3.5 Matrix Calculation and Data Mapping 36
2.3.6 Interpretation of Regression Equations 38
2.3.7 Vehicle-Prediction Calculations 39

TABLE OF CONTENTS (Cont'd.)

Page

3.0 VEHICLE TESTS 50

3.1 INTRODUCTION 50

3.1.1 Purpose 50
3.1.2 Scope 50

3.2 EQUIPMENT AND EXPERIMENTAL PROCEDURES USED 51

3.2.1 Test Stand Facilities Geared to the Project 51
3.2.2 Recycle System Made Simple 60
3.2.3 Carburetor Modifications 68
3.2.4 Distributor Modifications 68

3.3 RESULTS AND DISCUSSION 72

3.3.1 Operability of the Direct Recycle System is Good 72
3.3.2 Exhaust Gas Recycle Greatly Reduces NO_x Emissions 73

3.3.2.1 Chevrolet NO_x Emission 73
3.3.2.2 Plymouth NO_x Emission 78

3.3.3 Spark Timing and Recycle Both Affect NO_x Emissions and Fuel Economy 78
3.3.4 "Driveability" Sets a Limit on Recycle 85
3.3.5 Data are Quite Variable for Several Reasons 87

3.3.5.1 Recycle Gas Temperature 87
3.3.5.2 Humidity 88
3.3.5.3 Carburetor Design 88
3.3.5.4 Small Pressure Drops in Inlet Air System 90

3.3.6 Use of 4,000 Lb. vs. 4,500 Lb. Weights on Dynamometer Has Only Minor Effect on Results 91
3.3.7 Recycle Can Improve Fuel Distribution in Multicylinder Engines 92
3.3.8 Using Recycle "Continuously" Causes Higher CO and Hydrocarbon Emission 93
3.3.9 Bag Analyses Show Lower NO_x and Hydrocarbon Emissions 94
3.3.10 Recycle Can Be Used Without Serious Change in CO or Hydrocarbon Emission 95

3.3.10.1 Chevrolet Tests 95
3.3.10.2 Plymouth Tests 95

3.3.11 Vehicle Results Check Engine Lab Predictions 96

3.4 CONCLUSIONS 99

LIST OF TABLES

Table No.		Page
1.1	Engines Used in Steady-State Tests	13
1.2	Vehicles Studied Under Transient Operation Conditions	14
2.1	Speed-Load Combinations Studied in Steady-State Engine Tests	18
2.2	Dynamometer Break-In to Simulate 1,500 Mile Vehicle Break-In	22
2.3	Test Procedure	23
2.4	Exhaust Gas Instrumentation for Laboratory Engine Tests	30
2.5	Data Reduction Computer Program	32
2.6	Data Reduction Program Print-Out Lines	33
2.7	Weighting Factors for Contributions of Speed/Load Cases to Drive-Cycle Performance - 318 CID Plymouth	45
2.8	Predicted Relative Values - 318 CID Plymouth With 15.5 A/F Ratio During Recycle Use	58
3.1	Recycle Rate, Orifice Size vs. Vol. % on Air Rate	67
3.2	Effect of Spark Advance - California Cycle Data	84
3.3	Effect of Continuous Recycle on WOT Acceleration Times	86
3.4	Steady-State Data - Plymouth Car Emissions	90
3.5	Effect of Pressure Drop in Inlet Air System of Plymouth	91
3.6	Effect of Acceleration Weights - California Cycle Data	92
3.7	Effect of Recycle on Fuel Distribution - Plymouth	93
3.8	"Continuous" vs. "Automatic" Recycle	94
3.9	Bag Analyses vs. Analyses From Tapes	95
3.10	Lab Predictions vs. Vehicle Results (Plymouth)	98

LIST OF FIGURES

Figure No.		Page
2.1	Speed-Load Requirements of 4,000 Lb. Vehicle Under Specified Operating Conditions	16
2.2	USPHS Exhaust Recycle Program	25
2.3	Exhaust Gas Recirculation System	26
2.4	Flow Characteristics of Cornelius Recycle Valve	27
2.5	USPHS Exhaust-Recycle Program	37
2.6	The California Driving Cycle	41
2.7	Proposed Driving Cycle for Future Emissions Test Procedure	42
2.8	USPHS Exhaust-Recycle Program (Predicted Overall Effects of Recycle	46
2.9	USPHS Exhaust-Recycle Program (Predicted Overall Effects of Recycle	47
3.1	Clayton Dynamometer Stand #1	53
3.2	Clayton Dynamometer Stand #1	54
3.3	Exhaust Emission Test Report	55
3.4	Exhaust Emission Test Report	56
3.5	Car Operations Chart	57
3.6	Exhaust Gas Analysis	58
3.7	Cycle Tracer	59
3.8	Recycle Gas Inlet Plate	62
3.9	Recycle Gas Inlet Plate	63
3.10	Exhaust Gas Recycle System	64
3.11	Plymouth Recycle System	65
3.12	Chevrolet Recycle System	66
3.13	Spark Setting for Plymouth	69
3.14	Spark Setting for Plymouth	70
3.15	Spark Setting for Chevrolet	71
3.16	NO_x vs. Absolute Humidity	74
3.17	Adjusted NO_x vs. % CO	75
3.18	Adjusted NO_x vs. Recycle	76
3.19	Effect of Recycle on NO_x Emissions	77
3.20	Adjusted NO_x vs. % CO	79
3.21	Effect of Recycle on NO_x Emission	80
3.22	Adjusted NO_x vs. Recycle	81
3.23	Effect of Recycle on NO_x Emission	82
3.24	Effect of Spark Advance and Recycle	83
3.25	Effect of Humidity on NO_x Emission	89
3.26	Effect of Recycle on Hot-Cycle CO Emissions	97

SUMMARY

Previous studies showed exhaust gas recirculation to be an effective technique for NO_x suppression. The NAPCA-Esso study summarized in this report investigated:

- Feasibility of the recirculation technique when used in conjunction with positive crankcase ventilation and with the Engine Modification System or with Manifold Air Injection.
- Design characteristics needed for an automatic system to provide emission controls while retaining fuel economy and vehicle performance.

The goal was to determine the desirability of carrying out further studies concerning long-term operability, effectiveness and engine wear effects of exhaust recycle in combination with hydrocarbon and CO control systems.

The program was divided into two phases: a laboratory engine phase where four different engines were operated over a wide range of steady-state conditions and a vehicle test phase where two fully-equipped cars were studied under transient conditions.

Engines Used:

Plymouth	V-8	318 CID	Engine Modification
Ford	V-8	289 CID	Manifold Air Injection
Chevrolet	V-8	283 CID	Manifold Air Injection
Valiant	I-6	170 CID	Engine Modification

Vehicles Used:

Plymouth	V-3	318 CID	EM, 1967, Fury III
Chevrolet	V-8	307 CID	MAI, 1968, Impala

Laboratory Engine Tests

The laboratory engine work determined the effect of five independent operating variables on four dependent variables for each engine.

Independent Variables	Dependent Variables
Engine Speed	NO_x Emissions
Load (Torque)	CO Emissions
Air-Fuel Ratio	Hydrocarbon Emissions
Spark Timing	Fuel Consumption
Recirculation Rate	

The speed/load combinations investigated were chosen to cover the operation of engines at part-throttle conditions. Little exhaust is produced at idle settings and driving patterns include very little WOT operation. Moreover, both these modes occur with fuel enrichment which lowers NO_x emissions.

In general, recycle rates of 10-20% were found to lower NO_x emissions significantly and have minor effects on CO and hydrocarbon emissions and on fuel economy. The large amount of data obtained (five independent and four dependent variables for each of four engines) was computer processed to yield best-fit regression equations for each speed/load combination of the form:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_1^2 + B_5X_2^2 + B_6X_3^2 + B_7X_1X_2 + B_8X_1X_3 + B_9X_2X_3$$

where: Y is either the NO_x yield, HC yield, CO yield or fuel consumption relative to the base case (manufacturer's A/F, spark timing and 0% recycle) at that speed/load combination.

and X_1, X_2, X_3 are quasi-normalized values of A/F, spark setting and % recycle respectively.

Charts of the dependent Y variables vs. % recycle and spark setting were prepared at each A/F ratio for each speed/load case of each engine. A typical chart is shown in Figure 2.5. CO emissions were practically unchanged from those at base conditions (1500 rpm, 100 lb-ft torque, 30° spark setting, 15.4 A/F, 0% recycle) for this speed/load condition and are not plotted. The chart shows, for example, that at about 15% recycle and 5° spark advance (relative to base) NO_x emissions are reduced to about 35% of base levels, HC are up by 5% and fuel economy is improved by about 3%. Approximately 160 such charts were prepared. Some observations follow:

- Exhaust recycle reduced NO_x in all engines. Hydrocarbon emission was increased somewhat by recycle, particularly in the Valiant and Chevrolet. Recycle also raised CO slightly from the Chevrolet. Overall, recycle gave a small increase in fuel consumption.

- A/F ratio changes increased NO_x on approaching the stoichiometric ratio from either the rich (Chevrolet), slightly lean (Ford and Plymouth) or very lean (Valiant) directions. Leaning the mixture lowered HC emission in the Valiant and Plymouth, had little effect on the Ford and raised HC emission in the Chevrolet. CO emission was reduced by a leaner mixture in all engines. A leaner mixture decreased fuel consumption in the rich Chevrolet and increased it in the very lean Valiant--and had little effect in the Ford and Plymouth.

FIGURE 2.5

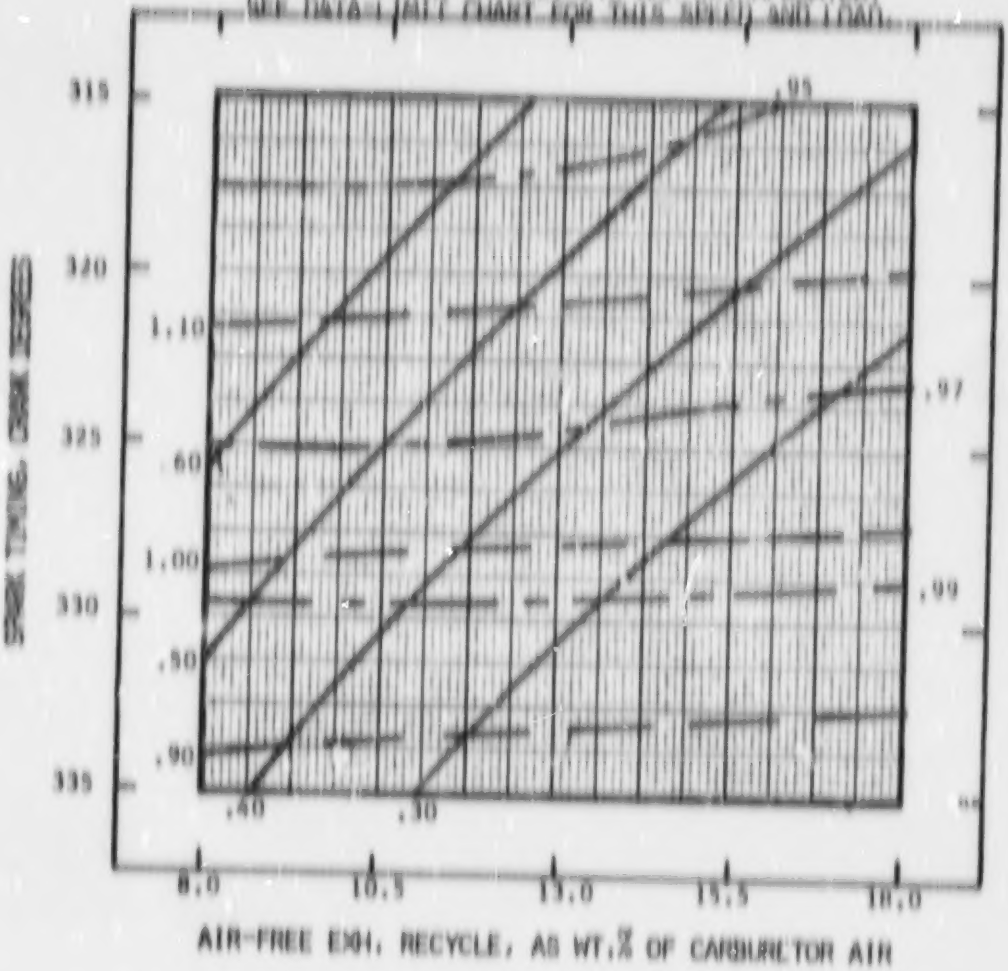
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth	ENGINE RPM 1500
CID 318	LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-H	A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3338	4057	PPM NO	97.8
REL. # C6HC/HR. (FID)	– – – –	0.4636	776	PPM C6	95.5
REL. # CO/HR. (Not Plotted)	-------	0.4588	0.23	%	97.6
REL. # FUEL/BHPHR.	– —— –	0.5379			95.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

- Spark retardation reduced NO_x by about 30% for each 10 degrees at zero recycle--the effect is less when recycle is used. Spark retard lowered HC and CO for the air-injected Chevrolet. The other engines showed only a slight decrease in HC. Fuel consumption was increased in all engines.

Vehicle Tests

In both cars, the recycle exhaust gas was tapped off upstream of the muffler and injected into the carburetor below the venturi and above the throttle plate. Thus, the driving force for recycle flow was primarily the muffler back pressure. Recycle flow rate was controlled at a set fraction of total flow by the insertion of a selected orifice in the recycle line. As the use of recycle leads to a lower manifold vacuum at a given speed/load condition, the hold-back springs on the vacuum-aspirated power jets were changed on both cars to prevent premature mixture enrichment. The cars could be operated without recycle, with continuous proportional recycle or in an "automatic" mode with proportional recycle only during part-throttle operation. Both steady-state and cyclic tests were run. For the cyclic tests, results were obtained either from transient analyses or from the "bag" of collected exhaust.

Operability of both recycle-equipped cars was good. NO_x levels were significantly reduced by recycle. Figure 3.17 summarizes the California hot-cycle data obtained with the Chevrolet. A cross-plot of these data and of similar data from the Plymouth is shown in Figure 3.18a. Approximately 10% inert recycle cuts the NO_x level in half for both cars. At 15% inert recycle, NO_x levels are down to 1/3 in the Plymouth and 1/4 in the Chevrolet.

Changes in A/F ratio, as mirrored by CO levels, noticeably affected NO_x values for the rich-running Chevrolet but had negligible effect on the leaner Plymouth. Ambient humidity had a significant affect on NO_x values from both cars: approximately 4% decrease in NO_x level for each 10 grain/lb. increase in humidity.

Interaction of exhaust gas recycle and spark setting on NO_x levels and fuel consumption is shown in Figure 3.24. For each car, data are presented with and without recycle and for three different spark schedules. (The "Mod-1" distributor has slightly advanced spark settings.)

The *patterns* observed for both cars were similar: exhaust gas recycle (at constant spark schedule) drastically lowered NO_x at a slight fuel consumption penalty, spark *retard* (at constant percent recycle) lowered NO_x at a higher fuel penalty. The effect of spark retard alone is about 6.5% reduction in NO_x per % fuel penalty compared to 16.5% reduction in NO_x per % fuel penalty for exhaust gas recycle alone. The two effects seem to be independent. It is, therefore, possible to operate with recycle and some spark *advance* to obtain NO_x reduction *without* fuel penalty.

FIGURE 1.17

ADJUSTED NO_x VS. % CO

Hot California Cycle - Chevrolet With Air Injection

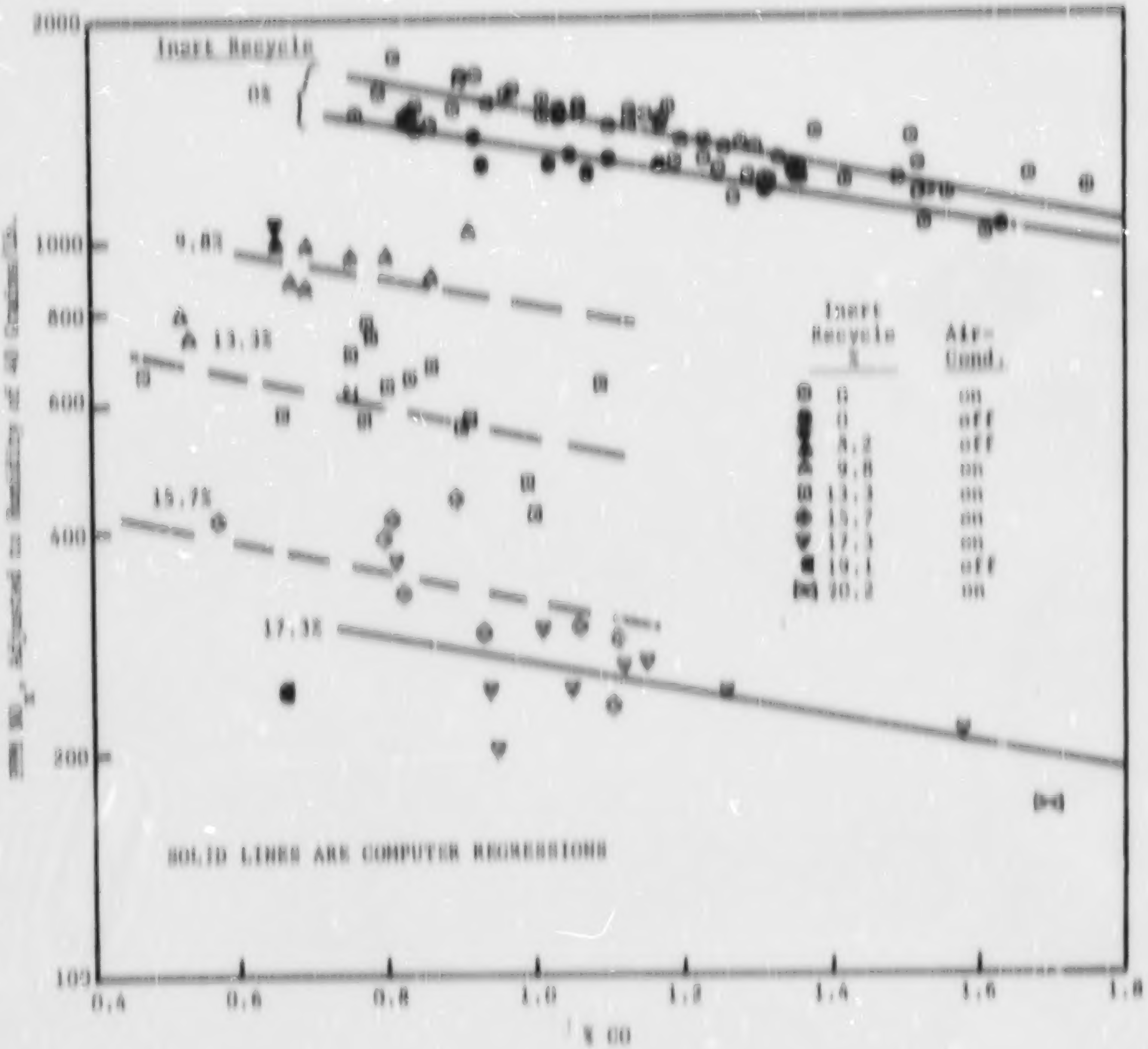


FIGURE 3.18a

EFFECT OF RECYCLE ON NOx

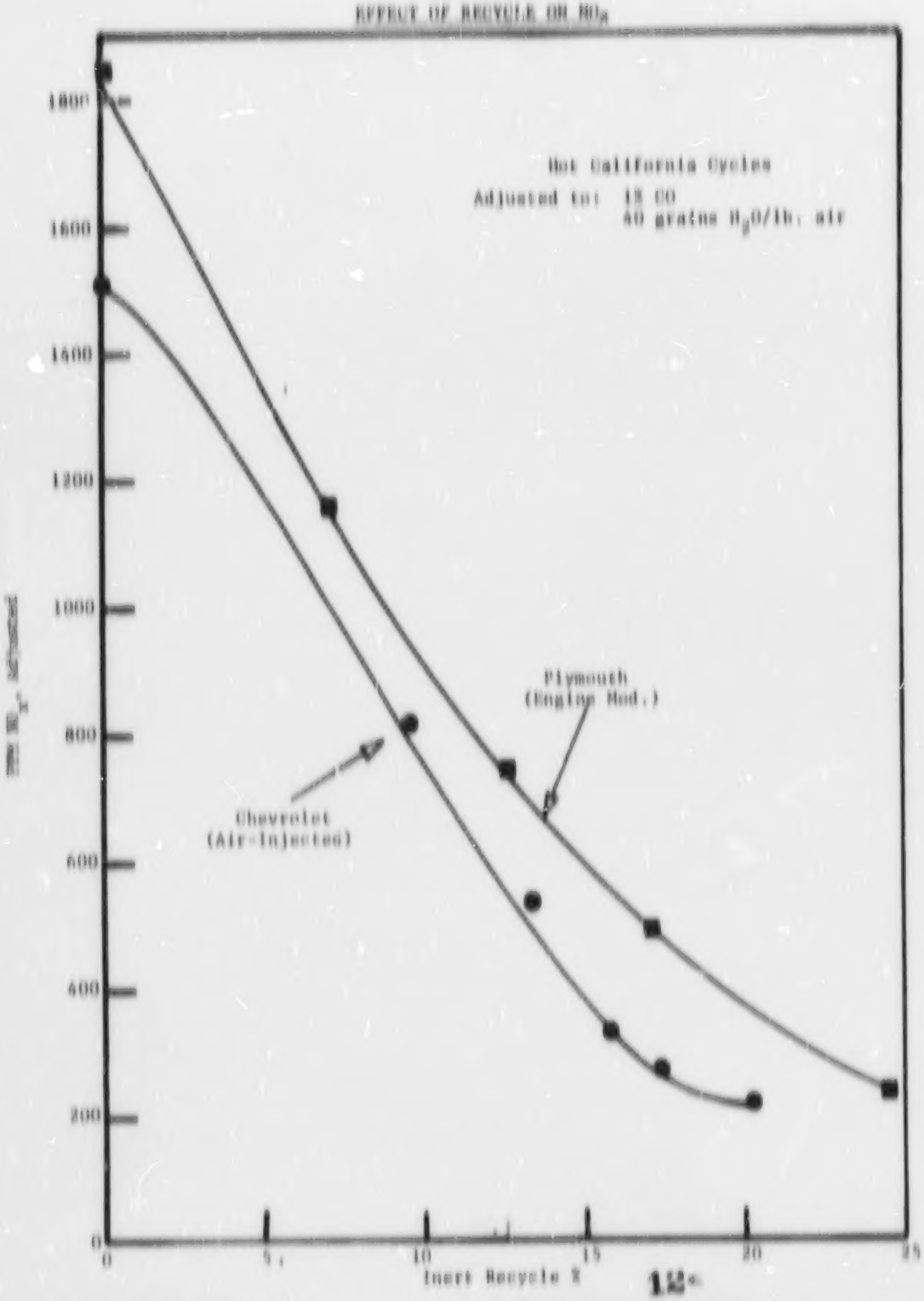
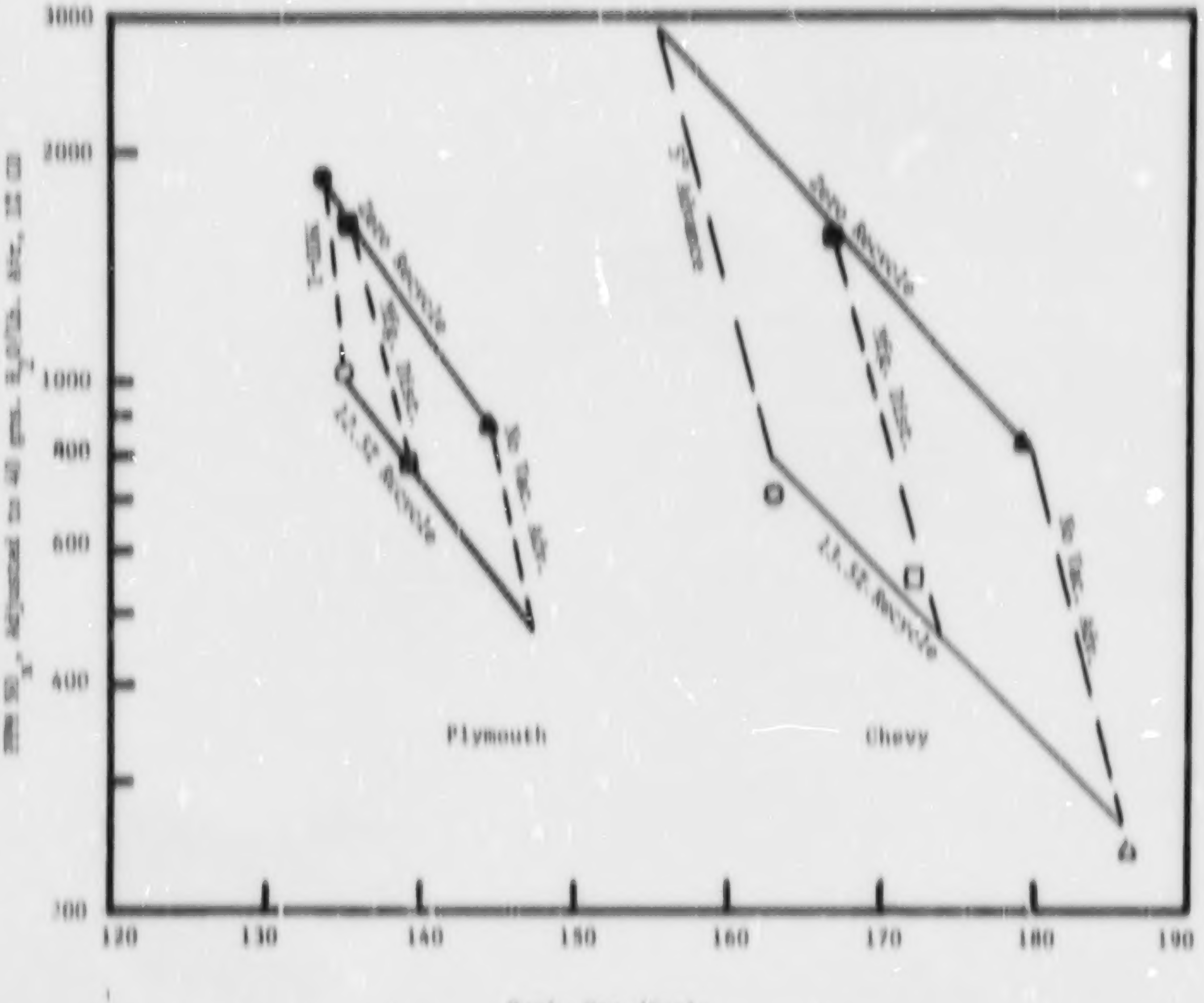


FIGURE 3.2A

EFFECT OF SPARK ADVANCE AND RECYCLE

California Cycle Data



The difference in fuel consumption levels between the two cars is presumably due to such factors as the Chevy running richer and being tested with the air-conditioner operating, while the Plymouth ran leaner and did not have air-conditioning.

Driveability, which showed only slight debits at around 13% inert recycle, was borderline at 16%. Cold starting tests (30°F) showed no deleterious effect at recycle rates below 15%. With 17% continuous recycle hesitation, bucking, etc., at WOT persisted for 0.5 to 1.0 mile further during warm-up than the 1.5 miles needed for 0% recycle operation. Use of an "automatic" recycle mode where recycle is omitted during idle, WOT and choked operation eliminates most of the driveability problems encountered with high rates of continuous recycle.

The effect of recycle on HC emissions was minor. Increases of 0-10% were usually observed in the Plymouth and decreases of 0-10% in the Chevrolet. The effect on CO was somewhat erratic with the Plymouth. Most runs showed changes of less than 15%, with decreases somewhat more frequent than increases. Some runs showed far greater increases. This variability was attributed to the high sensitivity of A/F ratio to exact throttle position and manifold vacuum. This sensitivity was also mirrored in occasional drastic variations in zero recycle CO levels. For the Chevrolet, back-to-back tests with and without recycle always showed lower CO with recycle. This was due to the extra air in the recycle gas which did not flow through the venturi to pick up its share of fuel. To maintain a given level of CO emission in a car with manifold air injection, slightly larger fuel jets should be used with recycle. For 1.0% CO, we found a 0.052" jet appropriate without recycle and a 0.053" jet proper for 10-14% inert recycle. Ideally, the transfer ports should also be changed when recycling.

Based on both the laboratory engine data and the vehicle data, exhaust gas recycle appears to be a suitable technique for NO_x control when used in conjunction with existing methods for CO and HC control. HC, CO, fuel economy and driveability debits, if any, are small. Suitable distributor and carburetor adjustments would be required to any production vehicles employing exhaust gas recycle. It appears desirable to investigate the long-term operability, effectiveness and engine wear effects of the combined emission control systems.

1.0 INTRODUCTION

The various undesirable air-pollution effects of automotive exhaust gas, apart from diesel fumes and the effluents of malfunctioning or high oil consuming vehicles, are related to the concentrations of carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x) present in the gas. The case against carbon monoxide rests on its toxicity and health effects related to the oxygen-transport efficiency of the blood. Unburned hydrocarbons, and particularly olefins, are undesirable because they participate with nitrogen oxides in a complex photochemical chain reaction leading to photochemical smog. Nitrogen oxides, besides their vital role in smog production, are toxic and cause coloration (yellowing) of the atmosphere.

All of these effects attributed to exhaust components become significant from a public health standpoint only when a combination of high vehicular traffic density and inadequate vertical mixing and outward dispersion of the exhaust contaminated air results in appreciable concentrations of the constituents for extended time periods. The existence of this combination in southern California has been recognized for nearly twenty years and the problems thus engendered have become progressively more acute as the population density increased. More recently, it has become apparent that this same combination and its attendant harmful effects exist to some degree in many other parts of the United States. In some areas where the problem is not presently acute, continued economic and population growth make the ultimate appearance of the problem inescapable unless positive steps are taken to prevent it. Thus the problem of automotive air pollution has grown national in scope and the attacks upon it through research, engineering, and legislation have also become nationwide. Because of their pioneering position in the attack on the problem, the techniques, procedures, and regulations developed in and for California have guided many of the developments made elsewhere.

The first automotive air pollution control technique was that of positive crankcase ventilation (PCV). In this system a slow stream of ventilating air, oil mist, and unburned fuel vapors (blowby gas) is drawn from the crankcase into the intake manifold for subsequent combustion. This mixture was previously vented to the atmosphere through the road draft tube. PCV was introduced in California in 1961 and, on new cars, throughout the United States in 1963.

Attempts to control air pollution from exhaust gas have centered largely on the control of CO and HC emissions. Even with this limitation, the problem has been substantially more difficult than the control of crankcase fumes. In spite of this difficulty, 1966 model-year cars sold in California, and 1968 model-year cars for nationwide sale, are equipped with systems that control CO and HC emissions at or below the California-defined standards in a specified test procedure. Further progress in the design and effectiveness of these systems can be expected in the future and may well be essential if the emission standards become more restrictive than they are today. The current systems are of two types. In the Engine Modification System, carburetion and ignition changes are used to maintain low emission. In the Manifold Air Oxidation System, carburetion and ignition are adjusted and supplemental air injected just outside the exhaust ports to oxidize CO and HC. Each engine-transmission combination differs in the adjustments required to meet the emission standards.

With control of the emission of CO and HC in automotive exhaust a foreseeable, if not yet accomplished, achievement, attention has been turned, in California and nationwide, to the control of emission of nitrogen oxides (NO_x). These oxides result from the high temperature fixation of atmospheric nitrogen in engine flames. It will be recalled that NO_x are objectionable, even without HC and photochemical smog, because of toxicity and air coloration. It is on these latter bases that the State of California has recently prescribed emission levels for NO_x down to 350 ppm from a vehicle operating in a specified test cycle. On the basis of currently available data, this implies a reduction of up to 75% from the average level of 1400 ppm.

Several methods are available for reducing nitrogen oxides:

- Recirculation of exhaust gas to the intake manifold.
- Injection of water into the intake manifold.
- Air-fuel mixture enrichment with excess fuel, particularly at part-throttle operation.
- Spark retardation.
- Lowering compression ratios.
- Use of catalysts to decompose nitrogen oxides in exhaust to nitrogen and oxygen.

Of these methods, exhaust recirculation shows the greatest promise. It provides a good level of control and is relatively simple to apply. Water injection is an effective method but would require that sizable quantities of water be carried and protected against freezing. Mixture enrichment is also an effective method but would result in loss in fuel economy. It would also nullify the Engine Modification System and may cause destructive overheating of the exhaust manifold with the manifold air injection system.

Retarding the basic timing, or decreasing the spark advance induced by inlet manifold vacuum, will lower the peak temperature and thus reduce NO_x. However, it will also decrease the power output per combustion event and thus increase fuel demand at a given duty cycle. Lowering compression ratio would result in a loss of performance and is a relatively less effective method of control than the other approaches listed. Published catalytic methods work well only when the system is on the fuel rich side of the stoichiometric air-fuel ratio. Thus they have the same disadvantages as the fuel enrichment approach. Additional disadvantages are that the catalyst would have to be replaced periodically and that lead anti-knock compounds might have to be removed from the gasoline with a resulting fuel cost increase. Exhaust gas recirculation, then, appears to be the most promising of the currently known methods for controlling nitrogen oxides emissions from vehicles.

Exhaust gas recirculation has been demonstrated to be an effective technique for NO_x suppression in a number of different studies. These studies bring out a number of the practical problems and limitations in its use and provide an invaluable point of departure for further developments. The investigations published up to now, however, needed to be expanded toward obtaining answers in the following areas:

1. Feasibility of the recirculation technique when used in conjunction with positive crankcase ventilation and with the Engine Modification System or with Manifold Air Oxidation.

2. Design features and parameters for an automatic system to provide an optimized combination of all the emission controls while retaining economy and vehicle performance.

3. The long-term operability, effectiveness and engine durability and behavior effects of the combination of systems.

The Esso-NAPCA Exhaust Gas Recycle Program was designed to encompass the first two areas, thereby determining the feasibility of investigating the third.

It was decided that the program objectives could best be achieved by dividing the program into two phases: a laboratory engine phase and a vehicle phase.

Laboratory Engine Phase

Four test engines were chosen (Table 1.1) as representative of American volume production engines and the then (1966) current approaches to meeting California exhaust emissions standards. These engines were operated at steady state in the laboratory to study the effect of speed, load, air-fuel ratio, spark timing and recirculation rate on CO, HC, NO emissions and on brake specific fuel consumption (BSFC).

The study of five independent variables in four different engines of necessity generated a large mass of data. In order to properly organize this data, a stepwise regression was performed for each speed-load condition of each engine.

The regression equations generated were able to predict more than 90% of the variance in the data. This greatly increased its usefulness by allowing extrapolation outside of the experimental range and by providing mathematical expressions which could be used in an optimization function. Optimization of these data for application to a vehicle was accomplished for driving cycles by assuming a carburetor flow curve, a distributor advance curve and by weighting the speed-load conditions for their occurrence in the driving cycle. The assumption of carburetor flow curves and distributor advance curves is a simplified method of introducing vehicle design constraints into the optimization calculations.

Vehicle Test Phase

The vehicle test phase was envisioned as a source of driveability data for the optimized system. However, shortly after the start of steady-state tests with the first manifold air injection engine (Chevrolet), it became apparent that the steady-state tests would not be sufficient to predict the transient response of this type of control system. Therefore, an enlarged vehicle program was designed to investigate some of the same independent and dependent variables as the laboratory engine study. It was, however, conducted in vehicles undergoing transient operation. The vehicles selected for use in this phase are shown in Table 1.2.

TABLE 1.1

ENGINES USED IN STEADY-STATE TESTS

Make	No. Cyls.	Disp.	No. Carb. Bbls.	Type Emission Control
Chevrolet	V-8	283 in.^{3}	2	A.I.R.$^{(1)}$
Ford	V-8	289 in.^{3}	2	Thermactor$^{(1)}$
Plymouth	V-8	318 in.^{3}	2	C.A.P.$^{(2)}$
Valiant	I-6	170 in.^{3}	1	C.A.P.

---

(1) Trade names for system using manifold air injection.
(2) Trade name for system involving only engine modifications, e.g., carburetor and distributor changes.

TABLE 1.2

VEHICLES STUDIED UNDER TRANSIENT OPERATING CONDITIONS

			Engine		
Make	Year	Transmission	No. Cyls.	Disp.	Emission Control
Chevrolet	1968	Automatic	V-8	307 in.^{3}	A.I.R.(1)
Plymouth	1967	Automatic	V-8	318 in.^{3}	C.A.P.(2)

---

(1) Air Injection Reactor - General Motors trade name for system using manifold air injection.

(2) Cleaner Air Package - Chrysler trade name for system involving only engine modifications, e.g., carburetor and distributor changes.

2.0 LABORATORY ENGINE PHASE

The Laboratory Engine Phase was designed to develop information in two areas:

1. Feasibility of the recirculation technique when used in conjunction with positive crankcase ventilation and with Engine Modification or Air Injection.

2. Design features and parameters for an automatic system to provide an optimized combination of all the emission controls while retaining economy and vehicle performance.

2.1 PROGRAM OUTLINE

2.1.1 Test Engines

Four engines were chosen as shown in Table 1.1 to be representative of 1966 production in terms of method of CO and HC control and sales volume. It was felt that the small displacement 6-cylinder engine would represent the most difficult test for the recirculation concept while the V-8's were the most popular engines from each of the major manufacturers.

2.1.2 Independent Variables

The major independent operating variables to be studied were:

- Engine speed
- Load (torque, output, air flow)
- Air-fuel ratio
- Spark timing
- Recirculation rate

2.1.3 Dependent Variables

At each setting of the independent variables, the following major dependent variables were recorded:

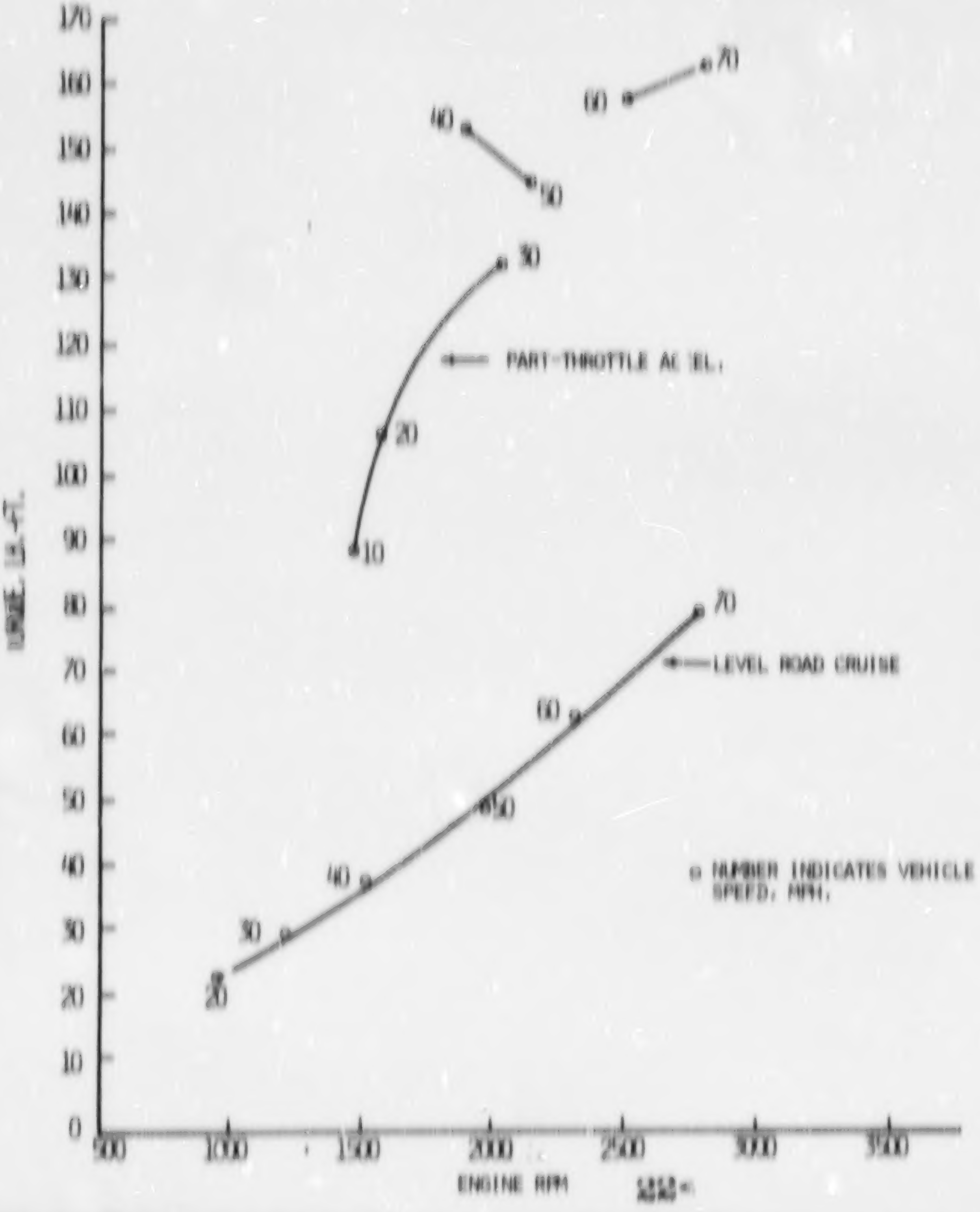
- Exhaust emissions: CO, Hydrocarbons, NO_x
- Fuel consumption

2.1.4 Selection of Speed-Load Conditions

Although speed and load are independent operating variables, their range is restricted by conditions encountered when operating the vehicle on the road. Therefore, for each engine, a group of speed-load conditions was selected which would blanket the spectrum of conditions encountered in road operation. A graph of driveshaft torque vs. engine rpm for two types of driving is shown in Figure 2.1. These data were supplied by the Ford Motor Company for a Fairlane with a 289 in.^{3} V-8 and automatic transmission.

FIGURE 2.1

SPEED-LOAD REQUIREMENTS OF 4000 LB VEHICLE
UNDER SPECIFIED OPERATING CONDITIONS



The level road curve represents the lowest power output for a given rpm with this rear axle ratio. The part-throttle acceleration curve is a fairly severe acceleration schedule used by Ford to evaluate fuel economy. Speed-load conditions for the California cycles would be intermediate between these two curves.

Two additional boundary conditions for speed-load selection were developed before the program began: (1) It was found that most of the NO_x production in the California cycle came during the acceleration and 30 mph cruise modes. (2) It was decided that in order to preserve wide-open throttle performance, there would be no recirculation at wide-open throttle. These two boundary conditions have corollaries which can be used to establish the actual operating limits.

An investigation of engine air flow and carburetor metering characteristics showed that at 30 mph cruise and for the majority of the accelerations the vehicle carburetor is operating on the plateau of the part-throttle metering curve. For the 289 in.^{3} Ford, 318 in.^{3} Plymouth, and 283 in.^{3} Chevrolet engines, the plateau of the part-throttle metering curve begins at a carburetor air flow of 2 to 2.5 lbs. per minute. NO_x production at lower air flows is limited because the air-fuel ratio becomes richer as air flow is reduced and the carburetor moves into the off-idle region of the operating curve and because in vehicle operation the speeds and loads are generally low at these air flows.

On current U.S. carburetors, the wide-open throttle metering curve is introduced as a step function of manifold vacuum. That is, whenever the manifold vacuum drops below 4-6 in. of Hg, the power jet opens to provide enrichment for maximum power output. It has been found that American cars operate at wide-open throttle for a very small percentage of their total operating time. This fact combined with the enrichment that occurs during this mode means that the quantity of NO_x produced under these conditions is relatively small compared to the quantity of NO_x produced in the part-throttle modes. Therefore, it was decided to eliminate recirculation at manifold vacuums less than 4-6 in. of Hg.

When these two additional boundary conditions are imposed on Figure 2.1, the typical operating range for these small V-8 engines is between 1000 and 3000 rpm. The upper limit of torque output is about 160 lb-ft and the lower limit is determined by the road-load curve and the low air flow constraint. Thus, as basic conditions for the laboratory engines, it was decided to run a range of loads at 2000 rpm and a range of speeds at 100 lb-ft of torque. Additional speed-load conditions were run as time permitted.

Similar considerations were applied to the 6-cylinder engine based on the data supplied by Ford for a Falcon equipped with a 170 in.^{3} engine. Here again, it was decided to run as basic conditions a range of loads at 2000 rpm and a range of speeds at 69 lb-ft of torque.

The actual speed-load conditions run with each engine are shown in Table 2.1.

TABLE [illegible].1

SPEED-LOAD COMBINATIONS STUDIED IN STEADY-STATE ENGINE TESTS

	Torque, Lb-Ft								
Speed, RPM	15	20	30	35	50	60	75	100	140
1000		V							
1500	V		V	F	V,C,F,P	V		C,F,P	P
2000			V		V,C,F,P	V	C,F,P	C,F,P	C,F,P
2500					P	V		C,F,P	P
3000					P	V		P	

C = Chevrolet, 283 in.^{3}

F = Ford, 289 in.^{3}

P = Plymouth, 318 in.^{3}

V = Valiant, 170 in.^{3}

2.1.5 Selection of Spark Timing

It was felt that the manufacturer's spark timing at each speed-load condition represented optimum timing for the no-recycle case. However, since charge dilution affects flame speed, optimum timing for the recirculation would probably be different than manufacturer's timing. Therefore, it was decided to establish the minimum spark advance for best torque (MBT) as a reference point for timing at each recirculation condition. Since advancing the timing beyond this point generally increased NO_x and hydrocarbon emission with no gain in power output, this represented the most advanced timing run at each set of conditions. It would have been most desirable to take data at MBT and at incremental timings retarded from MBT until the output power fell below a fixed level. However, in order to simplify the operating procedure and the data analysis, it was decided to investigate three spark timing settings at each combination of the remaining independent variables. In general, these timings were the minimum advance for best torque, 5° retard and 10° retard from MBT.

2.1.6 Selection of Air-Fuel Ratio

The respective engine manufacturers supplied a mean limit carburetor with each engine; i.e., a carburetor which represented the average of their production tolerance band. In general, when operating on the plateau of the part-throttle curve, air-fuel ratio delivered by the carburetor is dependent only on air flow. It was felt that the manufacturer's air-fuel ratio was the optimum for the no-recycle case. It was not clear how the air-fuel requirement might vary with recirculation; therefore, it was decided to use manufacturer's air-fuel ratio as the starting point for the recirculation cases and to vary the air-fuel ratio in one ratio increments.

The manufacturer's air-fuel ratio was leaner than stoichiometric for the Valiant, Ford and Plymouth engines. For these engines, operating one air-fuel ratio richer than manufacturer's condition generally increased CO emissions, hydrocarbon emissions and NO_x emissions, with only marginal increases in power output. Therefore, it was decided that the region leaner than manufacturer's A/F was most promising. In general, it was not possible to operate with recycle at two air-fuel ratios leaner than manufacturers. Therefore, there were generally only two air-fuel ratios investigated for these engines. However, in order to obtain a complete set of data on one engine, the Plymouth was operated at three different air-fuel ratios--one ratio richer than manufacturers, one ratio leaner than manufacturers and manufacturers.

Manufacturer's air-fuel ratio for the Chevrolet engine was richer than stoichiometric. In this case, it was found that leaner air-fuel ratios generally increased emissions with a loss in power. With this engine, the increase in CO and hydrocarbon emission with leaner air-fuel ratio seemed to be the result of decreasing oxidation efficiency in the exhaust manifold. Thus although CO and hydrocarbon emissions from the cylinder decreased with leaner mixtures, this was more than offset by the reduced oxidation efficiency. The net result being higher emissions from the system. The opposite effect was not encountered in the Ford, apparently because a one ratio enrichment increased emissions from the cylinder without significantly increasing oxidation efficiency in the exhaust manifold.

2.1.7 Selection of Recirculation Rate

In all cases, the recirculation rate has been defined as a percentage of the air flow through the carburetor. In early testing, it was found that recirculation rates less than 10 percent did not have enough impact on NO_x emissions to be of interest in the experimental program. However, the tolerance for recirculation varied with the speed-load condition and air-fuel ratio. Therefore, a nominal 10% recirculation was tested at each setting of the other independent variables. The rate was then increased in 5% increments, until misfire occurred in the engine or until the manifold pressure rose to 26 in. Hg absolute.

In general, 10%, 15% and 20% recirculation was tested under all conditions. However, under some conditions, difficulties were experienced with 10% recirculation while under other conditions as much as 30% recirculation was used.

2.1.8 Selection of the Recirculation Gas Temperature

It was expected at the start of the program that the recirculation gas temperature would be a minor but significant independent variable. It was felt that operation below the dew point without providing for condensate removal would create operational problems, while removing all water from the recirculated gas might decrease the effectiveness in controlling NO_x. At the same time, excessively high temperatures were expected to reduce the efficiency of the intake system and possibly cause problems due to excessive heating of the carburetor.

Previous data in the literature indicated that temperatures between 300°F and 500°F had no effect on NO_x control. Some limited initial testing confirmed that there was no apparent effect of temperature variation over this range. Therefore, it was decided to eliminate temperature as a variable but to operate at a moderately high temperature as more representative of conditions which might be encountered in the vehicle. Consequently, in all tests, with the exception of some early runs on the first engine (the Valiant), the recirculated exhaust was maintained at 400-500°F at the point where the gases entered the intake manifold.

2.1.9 Selection of Air Injection Rate

At the inception of the program, it was felt that recirculation might change the optimum rate of air injection for those engines equipped with air injection systems. However, preliminary tests with the Chevrolet engine (the first engine tested with air injection) indicated that the exhaust emissions were relatively insensitive to the air injection rate, both with and without recirculation. Therefore, the air injection rate was not treated as a variable in this study.

2.2 EXPERIMENTAL PROCEDURE

2.2.1 Break-in

The break-in procedure was designed to stabilize internal friction within the engine by simulating approximately 1,500 miles of road operation. Because of the difficulty of establishing and maintaining engine deposits, no attempt was made to simulate vehicle operation with respect to combustion chamber deposit accumulation.

The break-in procedure is shown in Table 2.2. Motoring friction was determined after steps 7, 8 and 9. If the friction levels were changing at the end of step 9 then step 8 was repeated until friction had stabilized.

2.2.2 Test Procedure

The speed-load conditions selected for each engine were run on a random basis in order to negate the effect of long-term changes in engine condition with time.

The recirculation rate, air-fuel ratio, spark timing matrix was not run randomly within each speed-load condition because of the uncertainties associated with establishing recirculation rate and air-fuel ratio. Although approximate levels of recirculation rate and air-fuel ratio could be established relatively easily, the time consumed and the error associated with trying to set a precise level (as opposed to measuring the level precisely) would have far overshadowed the benefits to be gained by randomizing these two variables. Therefore, the data within each speed-load condition were taken consecutively as shown in Table 2.3.

In order to minimize the effect of variations in engine condition with time, the dependent variables were measured at manufacturer's air-fuel ratio and spark timing at the beginning and end of each shift.

Mean limit carburetors were supplied by the manufacturers for each engine. Manufacturer's air-fuel ratio was determined by operating the engine at a variety of speed-load conditions with the mean limit carburetor and measuring air flow, fuel flow and exhaust gas composition. For test purposes, the mean limit carburetor was replaced with a variable jet carburetor. The air-fuel ratio at each test condition was established by adjusting the metering jet to give the desired exhaust gas composition. The exhaust gas correlations of Leonard(1) were used for adjusting air-fuel ratio in the test cell.

Mean limit spark timing as a function of speed and distributor vacuum was supplied for reach engine by each manufacturer. The spark timing was adjusted manually at each test condition.

---

(1) L. S. Leonard, "Fuel Distribution by Exhaust Analysis", SAE Paper 379A, St. Louis, June, 1961.

TABLE 2.2

DYNAMOMETER BREAK-IN TO SIMULATE 1,500 MILE VEHICLE BREAK-IN

Step No.	Time Per Step Hrs./Min.	Total Time Hrs./Min.	RPM	Intake Man. Vacuum In. Hg
1	0:30	0:30	1500	No Load
1a	Reduce engine speed and set tappets to prescribed hot setting if necessary. Adjust rocker arm stud nut to zero lash plus 3/4 of a turn.			
2	0:30	1:00	1750	12.0
3	0:30	1:30	2000	10.0
4	0:45	2:15	2500	8.0
5	0:30	2:45	2800	5.0
6	0:15	3:00	3000	WOT
7	3:00	6:00	3000	WOT
8	3:00	9:00	3000	WOT
9	6:00	15:00	1500	17.7

TABLE 2.3

TEST PROCEDURE

1. Set engine speed.
2. Adjust load to desired torque output at manufacturer's A/F ratio and spark timing.
3. Record data.
4. Introduce approximately 10% recycle - hold engine speed and air flow constant.
5. Adjust fuel flow to give desired air-fuel ratio.
6. Locate MBT spark timing.
7. Record data.
8. Retard spark 5° from MBT.
9. Record data.
10. Retard spark 10° from MBT.
11. Record data.
12. Repeat steps 5-11 until all desired combinations of A/F and spark timing have been tested at that combination of speed, load and recirculation rate.
13. Increase recirculation rate to approximately 15% - hold engine speed and air flow constant.
14. Repeat step 12.
15. Continue increasing recirculation rate until misfire is noted. Repeat step 12 at each speed, load, recirculation rate combination.

Note: 1. Follow same procedure for air injected engines, but turn air injection off to adjust air-fuel ratio.

2. Repeat manufacturer's base condition at the beginning and end of every shift.

The data recorded at each setting of the independent variables is indicated by the data sheet shown in Figure 2.2. A Cox nozzle was used to measure engine air flow, a Meriam laminar flow element was used to measure exhaust manifold air injection rate on air injected engines and a VDI orifice was used to measure recirculation flow rate.

The engines were run with the manufacturer's air cleaner and exhaust system including the muffler. This allowed for possible effects of the air cleaner on cylinder-to-cylinder distribution and of back pressure on NO_x emissions.

2.2.3 Recycle Flow Control

Several published techniques for introducing exhaust gas recycle were tried initially. None of these were satisfactory. A Cornelius valve supplied by NAPCA was then installed on the first (Valiant) engine.

The steady-state tests on the Valiant engine indicated that to be most effective the recirculated gas should be a constant fraction of the carbureted air at all speed and load conditions. A diagram of the Cornelius valve is included in Figure 2.3. The forces which position the Cornelius valve are quite complex. The primary determinates appear to be pressure drop across the orifice in the diaphragm and the unbalanced force due to the single poppet valve design. The pressure drop through the orifice in the diaphragm is a function of manifold vacuum and the size of the bleed restriction. In operation, the bleed restriction would be controlled by a tapered shaft connected to the throttle. However, for test purposes, this was replaced by a manually operated needle valve so that the size of the bleed restriction could be held constant at the desired setting.

The procedure for evaluating the ability of the Cornelius valve to maintain a constant recirculation rate was (1) set engine at 3000 rpm, (2) set throttle for desired air flow through carburetor, (3) set bleed restriction to give 10 percent recirculation, (4) reduce engine speed in 500 rpm increments to 1000 rpm holding bleed restriction and throttle position constant. After each incremental reduction, measure recirculation flow, carburetor air flow and intake manifold pressure.

The results of this evaluation are plotted in Figure 2.4. It is clear from these results that under these conditions flow through the Cornelius valve decreases much more rapidly with engine speed than does carburetor air flow. Therefore, the Cornelius valve does not appear to be a satisfactory device for automatically maintaining a constant recirculation rate.

Due to the complex nature of the control system on the Cornelius valve, it was concluded that it would be more efficient to use recycle flow control systems under development in parallel programs than to modify the Cornelius valve.

[illegible]

[illegible] EXHAUST RECYCLE PROGRAM

[illegible] GAS ANALYZER READINGS

REMARKS

FIGURE 2.3

EXHAUST GAS RECIRCULATION SYSTEM

(Test Set-up)

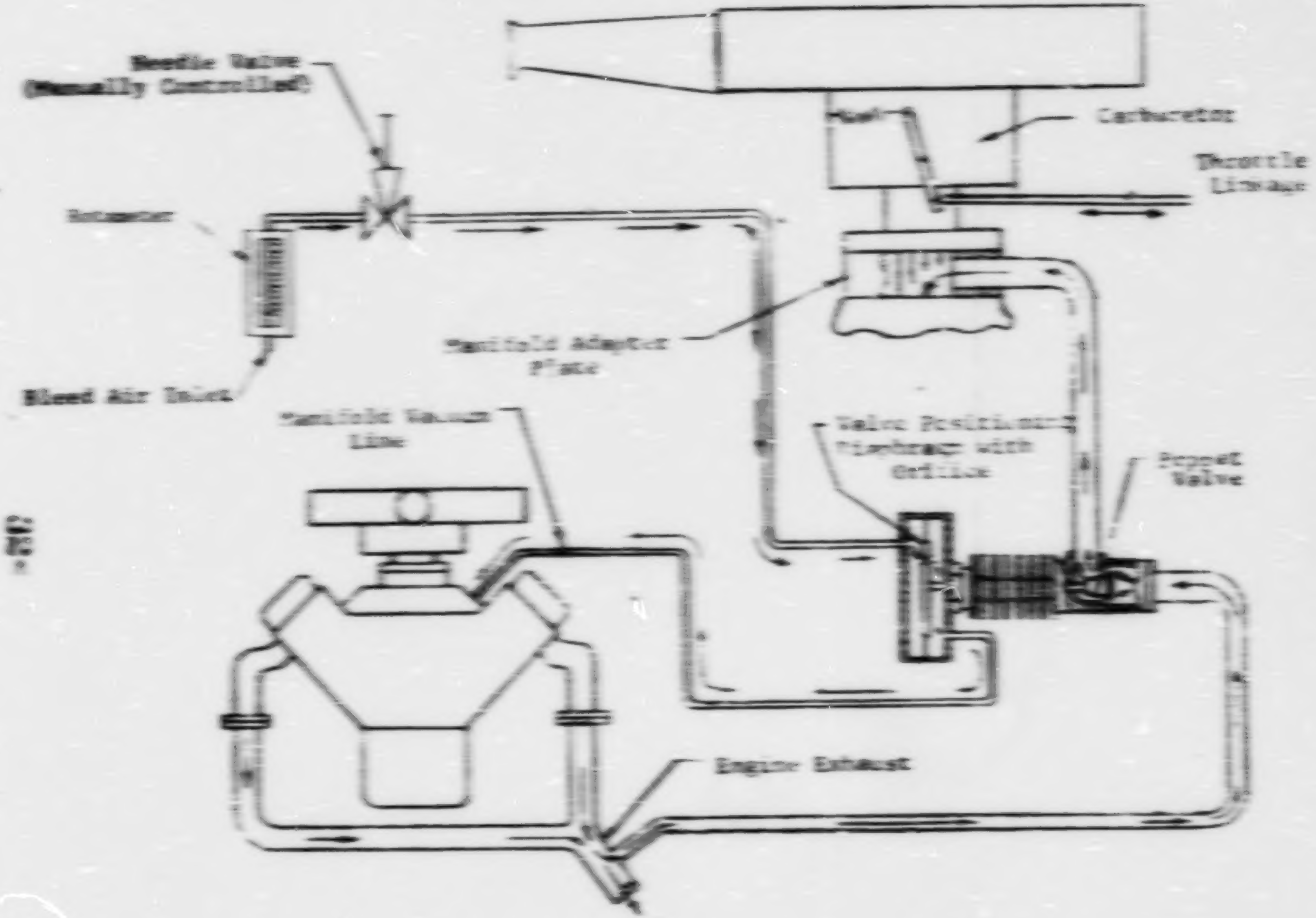
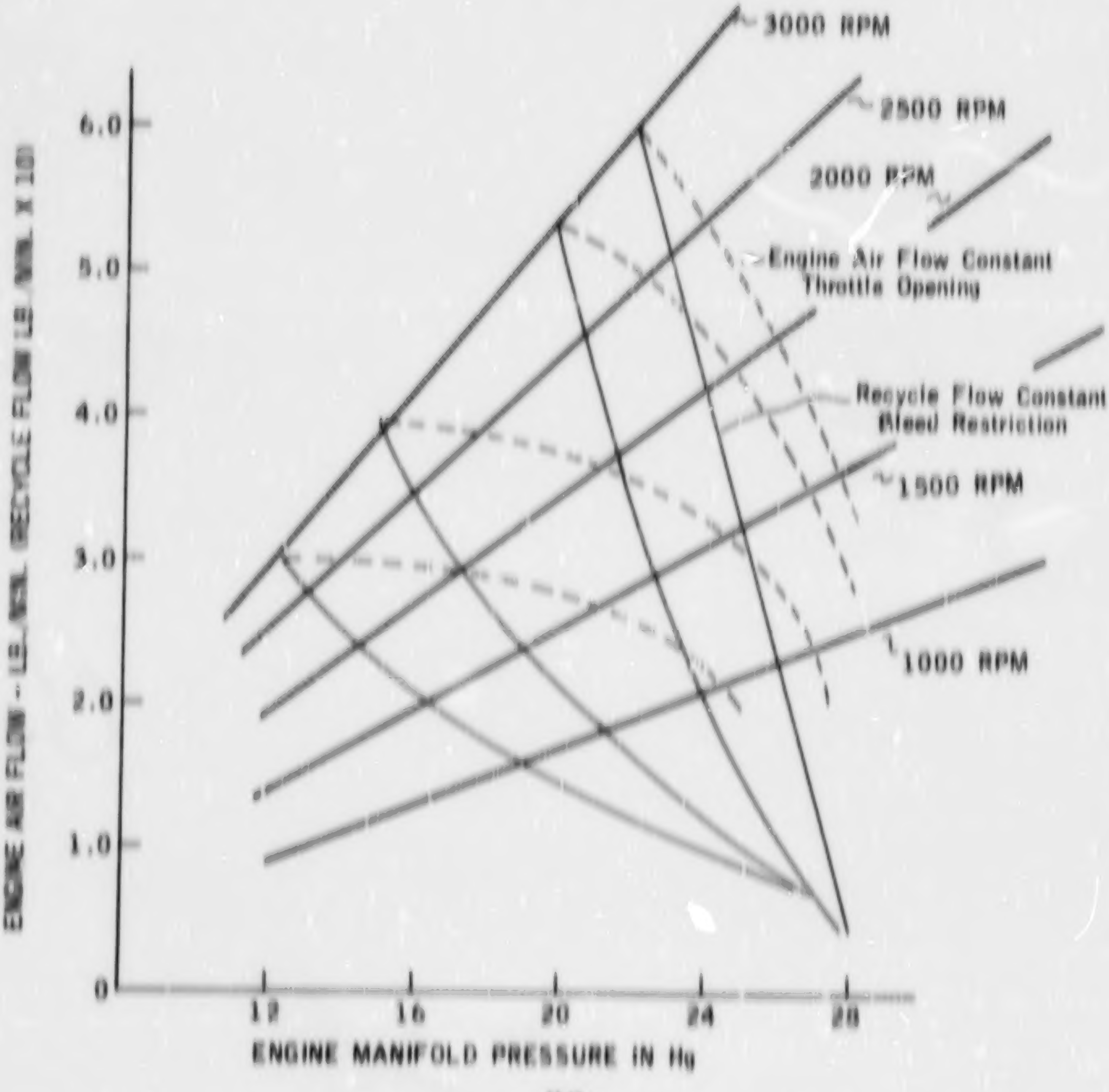


FIGURE 2.4

FLOW CHARACTERISTICS OF CORNELIUS RECYCLE VALVE



2.2.4 Instrumentation

2.2.4.1 Engine Speed and Load

The laboratory dynamometer shaft was rigidly connected to the flywheel of all test engines. The dynamometer used in this program has oil flotation bearings to support the rotor which allows a torque sensitivity of approximately 0.25 lb-ft. The field current is controlled through a variac so that speed is automatically held to the desired setting ± 10 rpm independent of load. In practice, the control action of the dynamometer coupled with minute variations in engine conditions causes the torque to oscillate over a range of about ± 1 lb-ft. However, by continuously recording torque, it was possible to read the mean torque output to within 0.5 lb.-ft.

2.2.4.2 Spark Timing

The flywheels of all test engines were inscribed in one degree increments beginning with 0 at top dead center and extending for 360 degrees. Timing was read manually using a strobe light triggered by the firing voltage in the number one cylinder.

2.2.4.3 Engine Air Flow Rate

Engine air flow was measured by flow nozzles mounted in a surge tank to eliminate pulsation effects. Six nozzles were used in order to cover a wide range of air flow (0.5 to 31.0 lbs./min.) without imposing undue pressure drop on the induction system (0.5 to 2.0 in H_2O range). Pressure drop across the nozzles was measured with a 48 inch inclined manometer graduated in 0.01 inch increments.

All engines were operated with the manufacturer's air cleaner. The flow nozzles metered air into the air cleaner and make-up air for the PCV system was taken from the air cleaner.

2.2.4.4 Engine Fuel Flow Rate

Engine fuel consumption was measured with a burette. A three-chamber burette was used which allowed fuel volumes of 100, 300, 400, 500, and 800 ml to be measured. The time interval over which the fuel consumption was measured was kept in the range of one to two minutes by selecting the appropriate size burette. This minimized the effect of reading errors on flow measurement. Fuel consumption was measured at least twice at each condition.

2.2.4.5 Exhaust Recirculation Rate

Exhaust recirculation rate was measured by a series of sharp edged orifices. The orifices were selected to have pressure drops in the range of 1 to 6 inches of water. Pressure drop across the orifice was measured with the same manometer used for inlet air.

Measured pressure drops through the orifice were obviously unreal during early tests due to pulsation in the exhaust system. After much experimentation the pulsation was eliminated by taking the exhaust for recirculation downstream of the muffler and using a throttling valve in the recycle line before the orifice to dampen any remaining effects.

2.2.4.6 Exhaust Gas Analysis

Exhaust gas from the test engines was sampled through a conventional sampling train involving ice water traps, type A filters, diaphragm pumps (teflon diaphragm) etc. The sample lines were purged with air when samples were not being taken.

The primary sample point for the total exhaust was immediately downstream of the muffler. In addition, sample taps were provided in each exhaust port and at the exit of each manifold to investigate distribution effects.

Details of the exhaust gas instrumentation are provided in Table 2.4.

TABLE 2.4

EXHAUST GAS INSTRUMENTATION FOR LABORATORY ENGINE TESTS

Function	Make and Model	Sample Cell Length	Range
Hydrocarbon Infrared	Beckman 315	13-1/2 in.	0-500 ppm C_6
FID	Beckman 108	--	Multiple
Carbon Monoxide	Beckman 315	1/8 in.	0-5 vol %
Carbon Dioxide	Beckman 315	1/16 in.	0-16 vol %
Nitric Oxide	Beckman 315	13-1/2 in.	0-500 ppm 0-2000 ppm 0-4000 ppm
Oxygen	Beckman 718	--	0-5 vol % 0-25 vol %

2.3 MATHEMATICAL ANALYSIS OF ENGINE-TEST DATA

2.3.1 Reduction of Raw Data

Raw data in the form of instrument readings, various pressures and temperatures, speed, torque, orifice-plate sizes, etc., for each speed/load case for an engine are keypunched on cards. Computer programs, which differ slightly for E-M and A-I engines, combine these data with stored characteristics of the fuel, air, exhaust-gas constituents, measuring instruments, and the test engine to yield useful computed results. The functions and output of the data-reduction program are listed in tables 2.5 and 2.6. For further use, the most important items in the output for a given speed/load case are the brake specific fuel consumption (BSFC), the mass emission rates of CO, NO_x (as NO_2), and FID-HC, the recycle rate (air-free, as wt % of carburetor intake air), the spark timing, and the air/fuel ratio.

2.3.2 Choice of Air/Fuel Ratio Calculation

Different A/F ratios are available for a given test. In all engines, the program computes the ratio of dry carburetor air mass rate to fuel mass rate as the "carburetor" A/F ratio. When recycle gas is in use, its oxygen content can be expressed as recycle air, and the computer calculates an "actual" A/F ratio, in which the mass rate of recycle "air" is added to that of carburetor air before taking the ratio to the fuel mass rate. The actual A/F may be as much as 1.3 ratios leaner than the carburetor A/F for an A-I engine at light load with a high recycle rate. For E-M engines, and for A-I engines when the air injection is defeated, exhaust-gas analyses can be used with the Leonard(1) nomograph or with the Spindt(2) equation to obtain two, usually different, A/F ratios values. The Leonard A/F was normally used, by the engine operator, for setup purposes without air injection or recycle while the carburetor, actual, and Spindt A/F ratios were calculated in the data-reduction computer program.

For data analysis and correlation, a choice is required between the available A/F ratio values. For A-I engines (Ford and Chevrolet) the logical choice is the actual A/F ratio, because it most nearly represents what is supplied to the engine as a combined result of carburetion, air-injector pump characteristics, and recycle rate. Carburetor A/F ratio reflects only one of these three factors, and the Leonard and Spindt ratios are not applicable because of air dilution and its effect on gas analyses. For the E-M engines (Valiant and Plymouth), the choice is between actual, Leonard, and Spindt A/F ratios. The actual A/F, involving a substantial number of measurements and

---

(1) L. S. Leonard, "Fuel Distribution by Exhaust Analysis", SAE Paper No. 379A, St. Louis, June, 1961.

(2) R. S. Spindt, "Air-Fuel Ratios From Exhaust Gas Analysis", SAE Paper No. 650507, Chicago, May, 1965.

TABLE 2.5

DATA REDUCTION COMPUTER PROGRAM

The program includes equations and tables for the following calculations and operations:

1. Fuel mass rate from burette volume, flow time and temperature and API gravity.

2. Carburetor dry intake air mass rate from humidity, temperature, barometric and Cox nozzle pressure drop data.

3. Carburetted A/F ratio from mass rates of fuel and carburetor air.

4. Actual A/F ratio (based on carburetor air + air in recycled exhaust gas) based on dry-gas analysis of exhaust, conversion to wet-gas basis, molecular weights of oxygen and of exhaust gas, and mass rate of recycle gas from orifice-plate size, pressure, temperature and pressure drop, corrected for molecular weight and Reynolds number of gas.

5. Spindt equation A/F ratio from exhaust analyses and fuel carbon content; not done for air injected exhaust.

6. Recycle gas rate, both total and air free, as weight % of carburetor air, from calculations in (4).

7. Injector air mass rate (A-I engines only) from Meriam calibration and pressure drop, corrected for temperature and pressure.

8. IR instrument reading conversions to % CO, % CO_2, ppm IRHC, and ppm NO by second order interpolations; % O_2 and FIDHC are direct from instruments; NO is corrected for CO and CO_2 effects if correct filter cells were not in use.

9. Pound-mole rate of total exhaust gas from fuel rate and carbon content and from CO, CO_2, and FIDHC contents of exhaust gas.

10. Mass rates of CO and NO_x (as NO_2) from analyses, molecular weights, and molar exhaust rate.

11. Mass rate of HC (FID) from fuel rate and fraction of total carbon ($CO + CO_2$ + FIDHC) appearing as FIDHC.

12. Brake horsepower, brake mean effective pressure and brake specific fuel consumption, from speed, torque, engine displacement and fuel rate.

13. Frictional torque from a derived equation using speed and manifold pressure; indicated mean effective pressure from brake and frictional torques and displacement.

Minor differences exist between programs for engines with engine modification and with air injection emission control systems.

TABLE 2.6

DATA REDUCTION PROGRAM PRINT-OUT ITEMS

1. Run No.
2. Code (run type)
3. RPM
4. Torque in lb./ft.
5. IMAP, "Hg
6. Mass rates of carburetor air and fuel
7. Carburetted A/F ratio
8. "Actual" A/F ratio (including air in recycle gas)
9. Spindt equation A/F ratio (not with air injection)
10. Spark timing in crank degrees
11. Brake specific fuel consumption, lbs./BHP-Hr.
12. Mass rates of FID HC, CO, NO_x (as NO_2).
13. Recycle rate as lbs./min. including any air present, and as wt % of carburetor air, both for total recycle gas and for air-free recycle gas.
14. Recycle gas temperature and pressure
15. Ambient air temperature and pressure
16. Exhaust composition, dry basis, as % O_2, CO, CO_2, and ppm FIDHC, IRHC, NO_x
17. Mass rate of air contained in recycle gas
18. Mass rate of air injected in exhaust (A-I engines)
19. Brake horsepower and brake and indicated mean effective pressures

error opportunities, is less attractive than the two available ratios based on gas analysis. Of the two, the use of the Leonard nomograph is simpler and avoids the Spindt equation's need for FID-HC analysis, fuel carbon content and a complex calculation best done in a computer. However, it has been shown by Broering(3) that the Spindt result agrees better than the Leonard with measured air and fuel rates under misfire conditions, where misfire was induced by grounding one spark plug terminal. Without misfire, the two were nearly equivalent in agreeing with measured rates. The Valiant engine uses very lean carburation, and it was felt that the use of recycle might give a substantial chance of misfire-type problems because of low flame speeds, although the effects of such misfire would be less pronounced than for a non-firing spark plug. On this basis, Spindt A/F ratios were used for the Valiant data. For the Plymouth, which uses nearer-stoichiometric carburation, the Leonard ratios were used in data analysis and correlation.

It is our experience, unlike that of Broering, that the Spindt and Leonard A/F ratios do not agree equally well with the actual A/F ratio, whether recycle is in use or not. Direct comparisons of the three ratios for over 150 randomly chosen Plymouth and Valiant no-misfire runs covering a wide A/F range show that the Leonard ratios range from 0.3 richer to 0.8 leaner (mean 0.23 leaner) than the actual ratios, with generally good agreement across the A/F range. On the other hand, the Spindt ratios range from 0.13 to 0.94 ratios leaner (mean 0.66 leaner) than the actual ratios, or an average difference of 0.43 ratios leaner by Spindt than by Leonard. A similar discrepancy between Spindt and Leonard ratios has been seen in recent data from cruise tests in a recycle-equipped Plymouth vehicle on a dynamometer and is found both with and without recycle in use. The origin of this discrepancy is unknown, but it is also found in 32 out of 40 runs in Spindt's own data if the Leonard nomograph is used with Spindt's gas analyses.

In view of the discrepancy between Spindt and Leonard ratios, it is important that one or the other be used consistently for handling the data from any given engine or vehicle, but the original choice is probably not critical.

2.3.3 Choice of Percent Recycle Calculation

A choice is also necessary for expressing the amount of exhaust gas recycled as a weight % of carburetor intake air; either the total recycle gas or the air-free gas may be used. In the case of A-1 engines especially, the air content can be more than 40% of the total gas. Since any air in the recycle gas, based on oxygen content is added to the carburetor air in calculating the actual A/F ratio (see above), it is appropriate to subtract it from the recycle gas, handling the latter on an air-free basis. Again, consistency in practice is probably more important than the original choice. Any control device for recycle will, of course, have to control the total gas, including any air that is present, just as any carburetor used will provide only a portion of the air available for combustion of the fuel.

---

(3) L. C. Broering, Jr., "An Evaluation of Techniques for Measuring Air-Fuel Ratio", SAE Paper No. 660118, Detroit, January, 1966.

2.3.4 Data Correlation by Regression Analysis

The objectives of the regression analysis include reporting of the multi-variant data in a comprehensible form, the guidance of recycle control system design for a vehicle installation and the prediction of vehicle emissions and fuel consumption when equipped for recycle. Analyses are carried out separately for each speed/load case for a given engine. The independent and dependent variables for each condition period are keypunched on data cards.

Independent Variables	Dependent Variables
A/F Ratio[4]	NO_x, as lbs. NO_2/hr.
Spark Timing	CO, lbs./hr.
Recycle (air free, wt % of carb. air)	FIDHC, lbs./hr. BSFC, lbs./BHP hr.

Base values of dependent variables for each speed/load case are defined by average results at manufacturer's specified A/F and spark, no recycle. The analysis correlates the relative (to base) values of the dependent variables with the independent variables. The independent variables are transformed to reduce their magnitudes to comparable small numbers around central values lying within the data range, as follows:

X_1 = (A/F − a)
X_2 = (Spark in crank deg. − b)/10
X_3 = (% Recycle − c)/5

where

	a	b	c
Plymouth	15.5	325	15.0
Chevrolet	13.5	325	12.0
Ford	15.5	325	15.0
Valiant	17.0	325	11.0

In addition, to allow non-linear and interaction terms to appear in the regression analysis, the following six derived variable were included:

$$X_4 = X_1^2;\ X_5 = X_2^2;\ X_6 = X_3^2$$

$$X_7 = X_1X_2;\ X_8 = X_1X_3;\ X_9 = X_2X_3$$

---

[4] A/F ratio bases:
Plymouth (EM) − Leonard nomograph
Valiant (EM) − Spindt equation
Ford and Chevrolet (AI) − (Carburetor air + air in recycle gas)/fuel rate

The regression equation model used has the form

$$Y_n = B_{n_0} + \sum_{i=1}^{9} B_{n_i} X_i,$$

where:

Y_1 = relative mass NO_x rate,

Y_2 = relative mass FIDHC rate,

Y_3 = relative mass CO rate, and

Y_4 = relative BSFC.

As defined above, variables, X_4-X_9 are not actually independent variables, since they are derived from X_1-X_3. (Other variables could be derived from X_1-X_3, but were not used in analysis of the recycle data.) The double precision stepwise regression program[5], however, treats all nine variables as independent, although it can give preference to specific terms, such as the first three (linear), if so instructed.

2.3.5 Matrix Calculation and Data Mapping

For each speed/load case, 5 values each of A/F ratio, spark timing, and % recycle are selected to bracket the experimental data. These values, suitably transformed to yield X_1-X_3 values, provide 125 points of a 3-dimensional matrix. The four regression equations (Y_1-Y_4) are solved for each point of the matrix, yielding 125 solutions for each of the 4 dependent variables, stated as relative emissions or BSFC, compared to the manufacturer's base values.

At selected A/F ratio levels in the matrix, contour maps are drawn for relative-yield levels at various values of spark timing and % recycle. The contour lines (4 sets, for 4 variables at each A/F) are defined by interpolation from the regression-equation solutions of the matrix points. The variable levels mapped are chosen to match the experimental levels as nearly as possible. Usually, 3 levels of A/F ratio are mapped except where data were restricted to only 2 levels. These maps are included in the Appendix. A typical contour map is shown in Figure 2.5

---

(5) Program 2507 of Esso Mathematics and Systems, Inc.

FIGURE 2.5

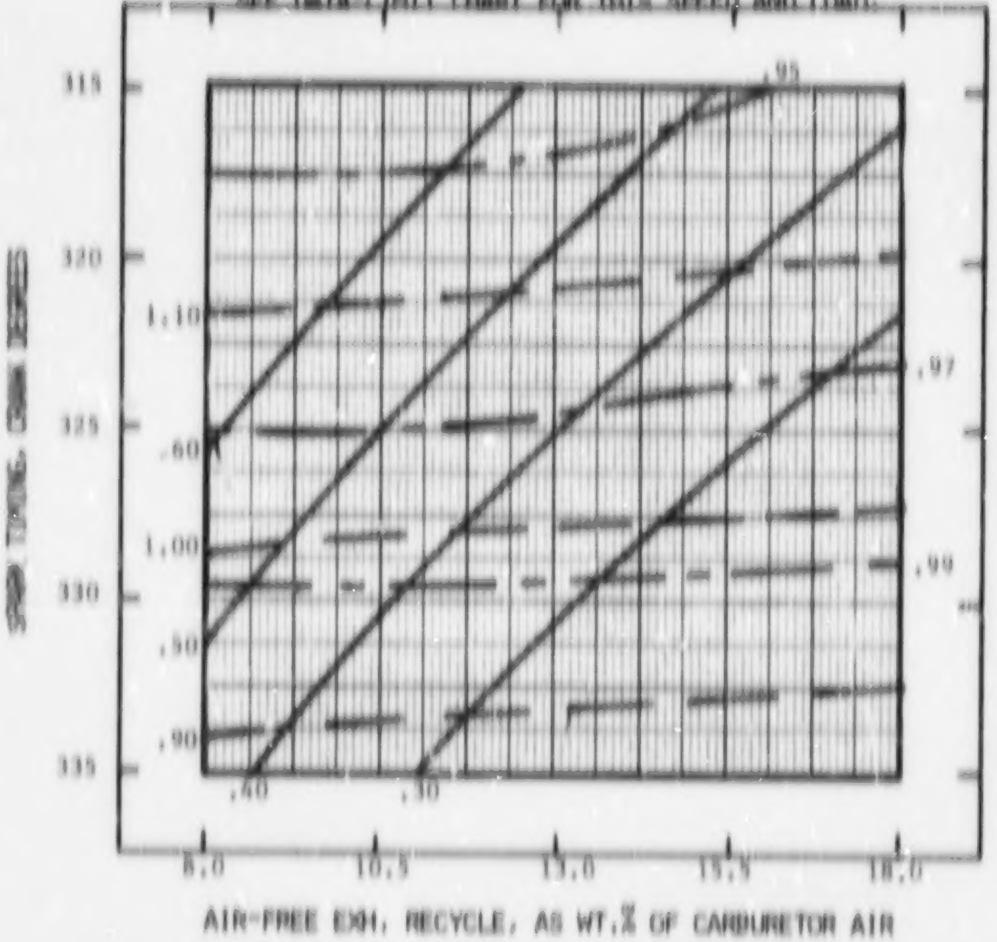
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-H A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━	1.3336	6057	PPM NO	97.8
REL. # C6HC/HR. (FID)	‒ ‒ ‒ ‒	0.6636	776	PPM C6	96.5
REL. # CO/HR. (Not Plotted)	-------	0.6588	0.23	%	97.6
REL. # FUEL/BHPHR.	‒ ── ‒	0.5379			95.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

2.3.6 Interpretation of Regression Equations

The regression equations were developed as best-fit descriptions of experimental data and have been used accordingly for the construction of Data-Contour Maps. However, the practical value of the equations lies in their ability to reflect known or reasonable functional relationships between engine variables and, as a result, to validly predict the performance of a recycle system installed in a vehicle. The equations include, in general, three linear-effect terms (B_1-B_3), three square terms (B_4-B_6) which introduce curvature, and three cross-product terms (B_7-B_9). The cross-product terms represent interactions which modify the linear effects of one variable as the second variable changes. Thus, the effect of spark retard on NO_x may be greater at one A/F ratio than at another, or the combined effects on NO_x of retarding the spark and using a high recycle rate may be less than the combined linear effects of the two variables would predict. A detailed evaluation of the various interactions is given in the Appendix. Some general deductions are given here.

The effect of A/F ratio on NO is to increase NO on approaching the stoichiometric ratio from either the rich (Chevrolet), very lean (Valiant) or slightly lean (Ford and Plymouth) directions. The three valid maxima lie between 15.0 and 15.4 A/F ratio, as expected. A leaner mixture lowers HC emission in the Valiant and Plymouth, has little effect in the Ford, and raises HC emission in the Chevrolet. The latter increase is apparently due to the decrease of heat-releasing CO so that the oxidation of HC in the air-injected exhaust is less complete. The Ford, which is already lean, depends less on its air-injection system for HC control. The maxima are reasonable for both E-M and A-I engines. CO emission is reduced by a leaner mixture in all engines, as expected. The lean Valiant has little sensitivity as expected, while the rich Chevrolet is not as sensitive to A/F as expected, presumably because in rich conditions there is substantial CO oxidation in the air-injected exhaust. Sensitivity of the Chevrolet CO to A/F ratio is much greater at appreciable recycle, where oxidation is poor. Again, the valid maxima and minima are reasonably located for the CO curves. A leaner mixture decreases fuel consumption in the rich Chevrolet and increases consumption in the very lean Valiant; it has little effect in the Ford and Plymouth; the minima are reasonable if account is taken of the adverse flame-speed effect of very lean mixtures. In summary, substantially all functional relationships with A/F ratio are in good agreements with known trends and directionally predictable from known principles.

Retarding spark timing reduces NO_x in the four engines by 24% to 38% for each 10 degrees of retard provided recycle is not used. The effect is increased for the Valiant and Chevrolet at A/F ratios near peak NO_x production, i.e., near stoichiometric, and is decreased in all engines if recycle is acting to suppress NO_x. These trends are to be expected. There is little curvature demonstrated, and computed maxima and minima are meaningless. Spark retard lowers HC emission because of the resulting hotter combustion-chamber walls and reduced flame-quenching. The Chevrolet is especially strongly affected because spark retard also raises exhaust temperature and thus favors injected-air oxidation of HC. Computed maxima and minima lie outside the data range and are probably meaningless. The small increases of CO with spark retard in the Valiant, Ford, and Plymouth are within prediction errors and not significant. The decrease in the Chevrolet CO with spark retard is in line with exhaust-temperature and oxidation effects. Spark retard increases fuel consumption in all engines, as expected. A minimum consumption at some advanced spark is reasonable and is seen in two of the four engines. The overall effects of spark timing on NO_x, HC, CO and BSFC, like those of A/F ratio, are thus consistent with known principles and are reasonable within the limits studied.

Exhaust recycle reduces NO_x in all engines. The effect is maximized at A/F ratios near stoichiometric (peak NO_x) and is reduced if the spark is retarded. The computed minima in NO_x at 21%-28% recycle are probably reflections of curvatures at lower recycle rates; very little data was obtained at rates in this range. Emission of HC is increased by recycle, particularly in the Valiant and Chevrolet. This may reflect lower wall temperature and, in the Chevrolet, lower exhaust temperatures and less effective air oxidation. Recycle also raises CO from the Chevrolet, probably for the same reason. Effects on CO in the Valiant, Ford, and Plymouth are smaller and probably within prediction errors; the base CO emissions in these engines are low enough that small changes are meaningless. The overall effects of recycle on fuel consumption are toward a small increase in consumption. However, in three of the four engines, there is an apparent minimum in fuel consumption at 2%-10% recycle. The coefficients contributing to this minimum tend to be derived from the lighter-load cases run in the engine, suggesting that the lowering of intake-manifold vacuum by adding recycle reduces pumping losses and thereby improves efficiency.

In summary, it is apparent that the regression equations, derived as best representations of experimental data, are also able in almost all cases to describe or predict the interdependence of the variables in ways which are either known to be valid from general experience with engines or are intuitively reasonable.

2.3.7 Vehicle-Prediction Calculations

Interest in the use of the regression equations to predict the emissions and fuel-economy of recycle-equipped vehicles in driving cycles was ultimately limited to the 318 CID Plymouth and the 283 CID Chevrolet. This limitation was imposed, at least in part, by the decision reached in the latter part of the engine tests to limit vehicle-system development and testing to these two engines. However, the steady-state engine test data and equations for the Chevrolet were felt to be unsuitable for predicting vehicle performance in a driving cycle because, as steady-state results, they strongly reflected the influence of recycle use on exhaust temperature and, thereby, on the oxidation effectiveness of the air-injection system for control of CO and HC emissions. Specifically, the Chevrolet engine data were taken after several minutes on each test condition, during which temperatures and emissions were leveling slowly to stable values. No other logical procedures could be selected under the circumstances. The results, however, cannot be the same as will occur in the transient modes of a driving cycle, where stable temperatures are rarely reached. For these reasons, only the performance of the Plymouth vehicle in cyclic operation was predicted from the regression equations.

The purpose of these calculations is the prediction of variations in mass emissions and fuel consumption, relative to the basic no-recycle vehicle, as A/F ratio, distributor-curve characteristics, and % recycle used are varied, with the vehicle performance evaluated in a standardized driving cycle. Such predictions should permit the selection of optimum conditions without conducting a multi-variable vehicle test program. At least two driving cycles, involving different engine conditions, should be predicted in order to avoid selecting as optimum a distributor-carburetor-recycle combination that is unique to one cycle and not suitable in other circumstances.

The two driving cycles predicted are (a) the 137-second California or Federal cycle, in which 68 selected seconds are weighted and the others ignored and (b) the 127-second self-weighting USPHS-developed driving cycle, for which all seconds are included. Figures 2.143 and 2.144 show the mph/time relations during these cycles. For the USPHS cycle, mass emissions in the cycle can be defined, on a relative basis, by the total of the products of volume or mass air flow and pollutant concentration in each second, with each second thus making a definable fractional contribution (different for each pollutant) to the overall mass emission. For fuel consumption, each second has a measurable volume or mass air flow rate associated with it. This flow rate represents a fraction of total air flow and this same fraction is assumed to apply to fuel flow in that second.

For the California cycle, the pollutant concentrations are read every second during 68 selected seconds. Prior to summing these concentrations, they are weighted by factors representing (a) the fractional contribution of the particular driving mode to the total exhaust volume of a vehicle in an urban driving pattern and (b) the fractional contribution of the particular second involved to the number of seconds for which that driving mode is sampled. For example, 0.455 of all the exhaust volume in an urban driving pattern is emitted during accelerations characterized by the "15 to 50 mph" acceleration mode. Twelve seconds of this mode are sampled when calculating a California cycle. The pollutant concentration for each of these twelve seconds is thus multiplied by (0.455/12) = 0.038 to give the pollutant contribution attributable to that second. Fuel consumption in the California cycle (counted seconds only) is also weighted, for each second, on the basis of air flow, as was done for the USPHS cycle.

FIGURE 2.6

THE CALIFORNIA DRIVING CYCLE

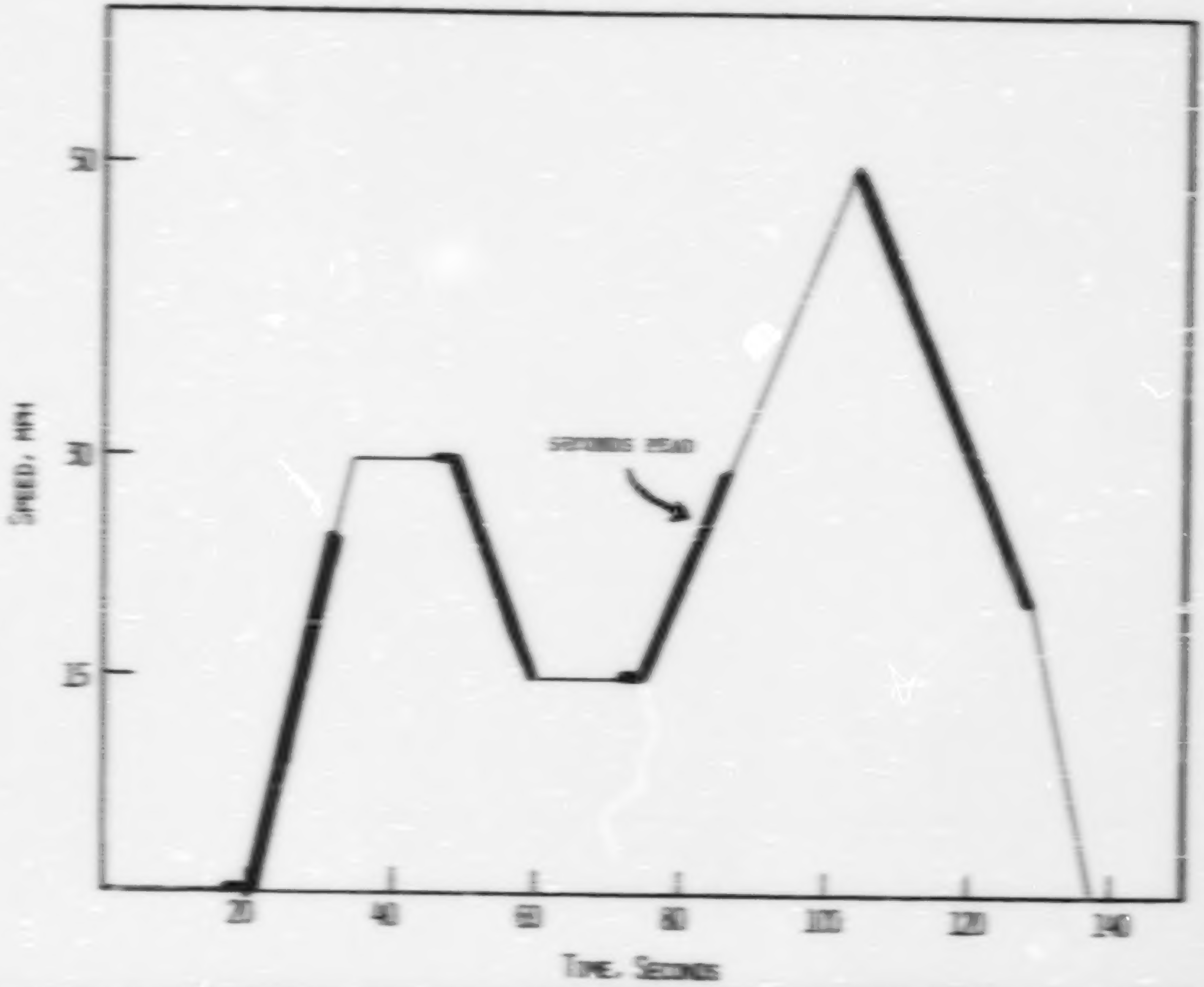
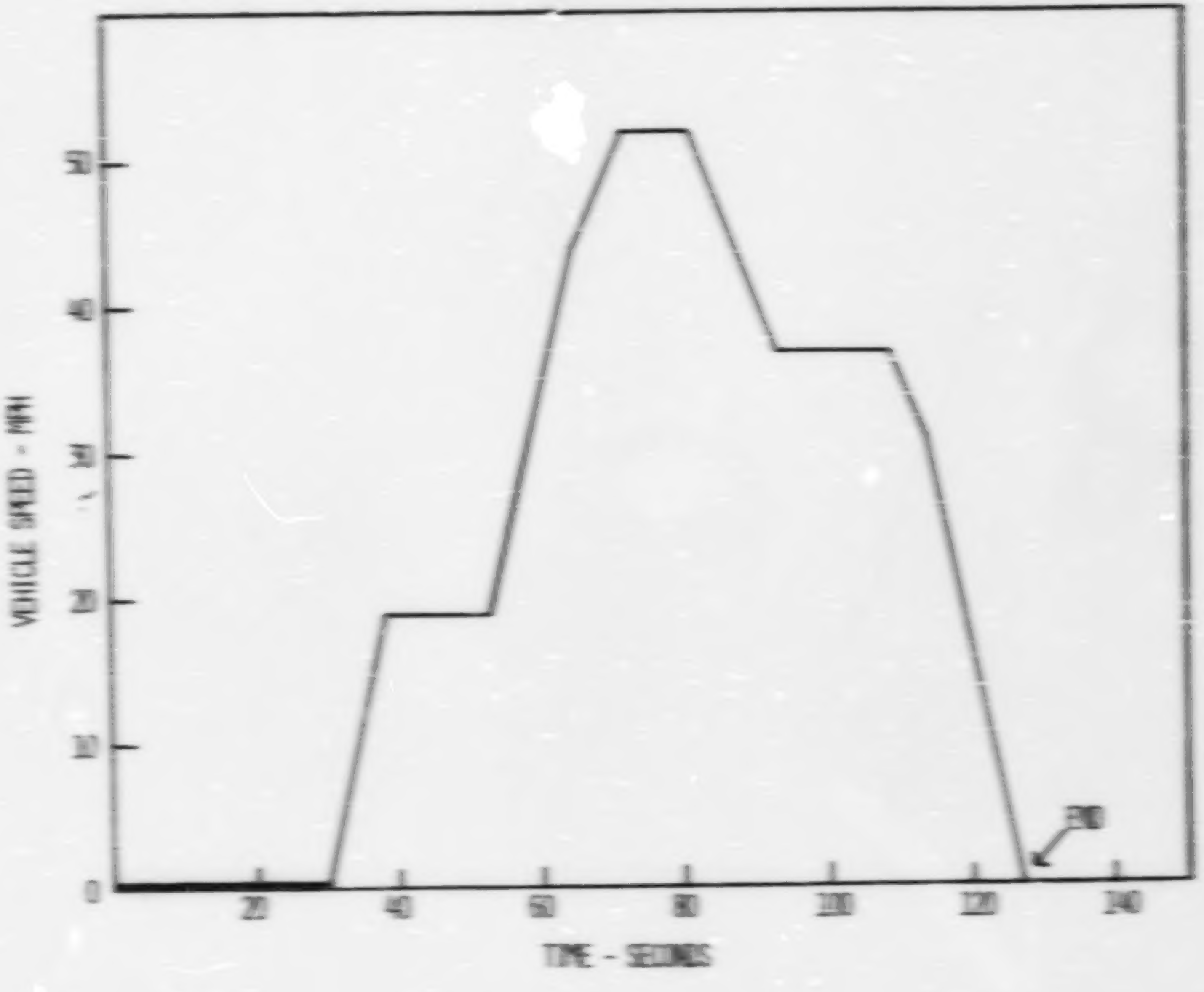


FIGURE 2.7

PROPOSED DRIVING CYCLE FOR FUTURE EMISSIONS TEST PROCEDURE

[illegible] Cycle



Regression equations for the performance of a cold engine with recycle were not available. Therefore, the predictions are for hot-cycle operation only.

The air-flow and pollutant-concentration data needed for describing each second of both cycles were obtained by operating a 1966 Plymouth (318 CID, emission controlled by CAP system) in the test cycles on a Clayton chassis dynamometer. The vehicle was equipped with a standard distributor, a flow-tested carburetor, and a recording intake-air meter. For consistency with engine test data, the hydrocarbons were measured by FID as well as the usual NDIR method. NDIR was also used for NO_x, CO, and CO_2. The FIDHC results were used in the weighting calculations for HC emissions. Engine RPM and manifold pressure were recorded during the cycle operations.

Using the recorded speed, manifold pressure, and air-flow rate, each second in a driving cycle is defined as being best-represented by a speed/load case from the steady-state engine tests in which recycle is used, or as being at too low an air-flow rate (below 2.0 lbs./min.) for recycle to be used. Those seconds in which recycle is not used, and their emissions and fuel consumptions, are assumed to be unaffected by the recycle system and are carried forward without change into the predictions. Each second in which recycle is to be used has its emissions and fuel consumption modified by the four regression equations for the speed/load case to which it has been assigned. All seconds make fractional contributions to the total emissions and consumption as defined by the calculations described above.

Because it is assumed that recycle is in use only above a certain air-flow limit, only a part of the total pollutant emissions and fuel consumption can be influenced by recycle, as shown in the following table.

	% of Total Occurring During Use of the Recycle System(a)	
	California Cycle	USPHS Cycle
Mass NO_x Emission	94	88
Mass HC Emission	75	54
Mass CO Emission	60	64
Air (Fuel) Flow	84	67

(a) I.e., above 2 lbs./min. air flow to carburetor.

The table indicates upper limits of 94% and 88% on NO emission control from recycle use. Each number in the table is made up of sub-divisions corresponding to the relative contributions made when operating at or near conditions matching a specific steady-state speed/load case from the engine studies. The California cycle is matched by using steady-state data from 6 different cases, while the PHS cycle is matched by using 7 cases. Each case contributes by a different amount to each pollutant and to fuel consumption. The portions of the driving cycles when recycle is not in use make fractional contributions given in % by (100 - each of the above numbers). The weighting factors are given in detail in Table 2.7

The regression equations for each variable (relative NO, HC, CO and BSFC) in each speed/load case can thus be weighted in proportion to the fractional contribution of each case to the total for the driving cycle. (The contribution of a given case to total NO differs from its contribution to total HC, etc.) Similarly, the emissions and fuel consumption during those parts of the drive cycle where recycle is not used have a defined weight and an associated "relative yield" value of 1.0, since recycle is not influencing them. It is further assumed that the spark and A/F ratio are not changed in these no-recycle conditions. The sum of the weights for all cases and for zero-recycle is 1.000 for a given pollutant or for fuel consumption.

The overall relative performance in the driving cycle is then given by the sum of the products of individual weights and relative yields, where the yields are either calculated by the regression equations from the steady-state tests, or are given by 1.0.

Inputs to the regression equations for each speed/load case are required. These are defined as (1) 5 values of A/F ratio to be used during recycle use, (2) 5 values of % recycle, and (3) 4 spark timings selected from defined curves, using engine speed and manifold vacuum. The manifold vacuums are those obtained with about 14% recycle gas rate. Four vacuum-advance curves were defined as shown in the following table:

Curve Designation	Vac. Adv., Deg.	Man. Vac., "Hg		Slope, Deg./In. Hg
		Start	End	
Mfr. Std.	24	9	16	3.43
Mod-1	24	4	16	2.00
Mod-2	24	6.5	13.5	3.43
Mod-3	24	4	11	3.43

The centrifugal advance characteristics of the original distributor are retained, but the start, end, and slope characteristics of the vacuum-advance system are varied. (The use of earlier spark timing with recycle is made desirable by the slower burning of the exhaust-diluted mixture.) For a given distributor, predictions are thus made for 5 levels of recycle and 5 A/F ratios. When recycle is not in use (low air flow) the spark timing and A/F ratio are at the manufacturer's standard values.

For each driving cycle and distributor curve, the 25 values of each of the four output variables provide the data for constructing eight driving-cycle prediction maps. The contour lines on each map are drawn by interpolation between the computed values, which form a 5 x 5 grid for each output variable. Typical prediction maps are shown in Figures 2.8 and 2.9. The remainder are given in the Appendix.

TABLE 2.7

WEIGHTING FACTORS FOR CONTRIBUTIONS OF SPEED/LOAD CASES TO DRIVE-CYCLE PERFORMANCE - 318 CID PLYMOUTH

Case No.	RPM/Torque	No. of Secs. in Drive Cycle		California Cycle				USPHS Cycle			
		Calif.	USPHS	NO_x	HC	CO	Fuel	NO_x	HC	CO	Fuel
1	1500/50	3	20	0.142	0.126	0.068	0.095	0.095	0.103	0.136	0.096
2	1500/75	1	4	0.016	0.021	0.021	0.020	0.058	0.046	0.025	0.042
3	1500/100	16	3	0.714	0.558	0.494	0.643	0.051	0.042	0.033	0.038
4	1500/140	2	4	0.070	0.045	0.022	0.082	0.077	0.070	0.108	0.069
6	2000/75	—	6					0.179	0.064	0.059	0.087
8	2000/140	—	13					0.365	0.192	0.255	0.306
9	2500/50	—	2					0.059	0.020	0.018	0.030
None	(Low air flow)	46	75	0.058	0.251	0.395	0.158	0.116	0.464	0.367	0.329
		68	127	1.000	1.001	1.000	1.000	1.000	1.001	1.001	1.000

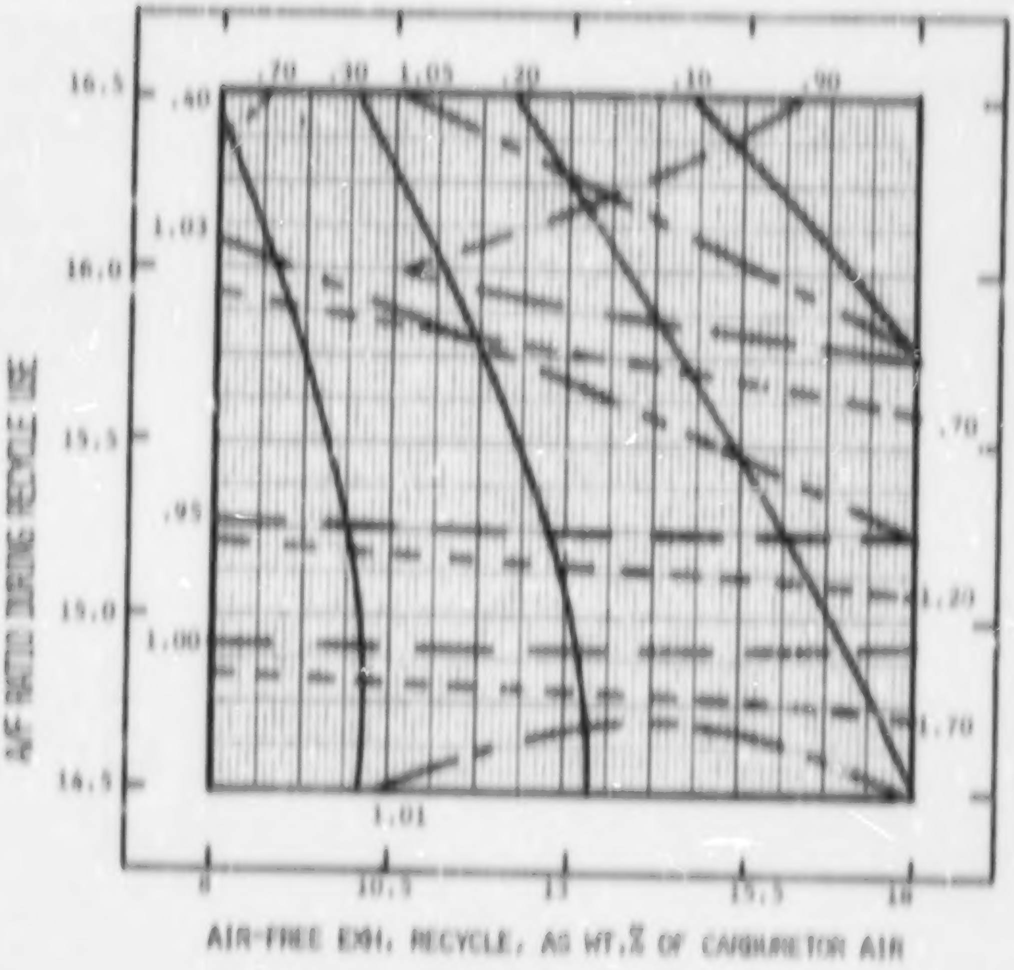
FIGURE 2.8

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR

Plymouth VEHICLE IN California DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mfr - Std.



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE. (Counted seconds only).

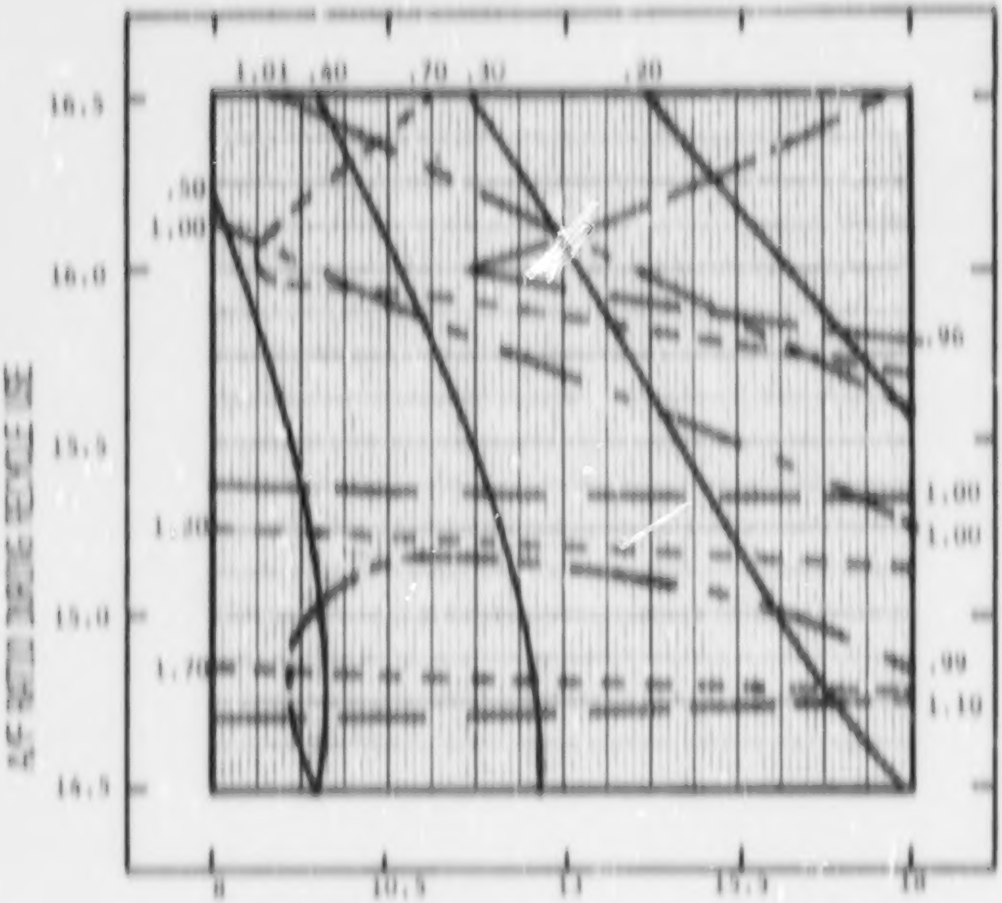
——————— NOx
— — — — HC (FID)
— - — - — FUEL CONS.
- - - - - - CO

FIGURE 2.9

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN California DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE,

SPARK CURVE ASSUMED: Mod-1



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE. (Counted seconds only).

——————— NOx
— — — HC (FID)
— - — - — FUEL CONS.
- - - - - - CO

TABLE 2.8

PREDICTED RELATIVE VALUES - 318 CID PLYMOUTH WITH 15.5 A/F RATIO DURING RECYCLE USE(a)

Driving Cycle(b)	Spark Curve	Values Relative to Base Vehicle Without Recycle							
		NO_x		FID-HC		CO		Fuel Cons.	
	% Rc:	13	15.5	13	15.5	13	15.5	13	15.5
California	Mfr.-Std.	0.272	0.195	0.918	0.916	0.831	0.792	1.025	1.021
	Mod-1	0.351	0.273	0.981	0.979	0.875	0.835	0.996	1.000
	Mod-2	0.420	0.332	1.025	1.023	0.911	0.872	0.985	0.990
	Mod-3	0.458	0.372	1.047	1.044	0.932	0.893	0.973	0.977
USPHS	Mfr.-Std.	0.266	0.206	0.962	0.972	0.847	0.833	1.037	1.048
	Mod-1	0.371	0.303	1.026	1.036	0.875	0.859	1.012	1.022
	Mod-2	0.352	0.286	1.015	1.024	0.871	0.855	1.018	1.028
	Mod-3	0.443	0.389	1.082	1.092	0.895	0.880	0.995	1.006

(a) Without recycle (low air-flow), A/F ratio and spark remain at base-vehicle values.

(b) In the 137-second 7-mode California cycle, 68 seconds are used and the remainder disregarded. In the 137-second 8-mode USPHS cycle, all seconds are used.

A selection of the computed values at 15.5 A/F ratio and two levels of recycle is reproduced in Table 2.8 for three pollutants and fuel consumption and for four different vacuum-advance spark curves. The table shows that there is relatively little difference between the two driving cycles, so that the selection of an optimum control system should have general validity under all driving conditions. As expected, the control of NO_x is sensitive to both recycle rate and spark timing. Spark timing has a substantial effect on fuel consumption and emission of CO and HC; but, in this range at least, recycle rate has little effect on these variables. There is, of course, a substantial effect of A/F ratio, particularly on CO emission. This effect and a broader range for the other variables can be seen on the contour maps.

The computational techniques presented here for the performance of a vehicle in a driving cycle could, in principle, be applied to the Valiant, Ford, and Chevrolet data if the necessary vehicle tests were carried out for weighting-factor definition. This has not been done for the reasons discussed previously. For the air-injected Ford and Chevrolet, the steady-state engine-test data and resultant regression equations do not take account of the effect of rapidly varying temperatures in the transient operation found in the driving cycles and in normal vehicle operation. The effect of the injected air depends strongly on these temperatures. Moreover, the regressions and predictions when air injection is used are on the basis of A/F ratio values that include both carburetor air and air in the recycled exhaust gas. Since this latter can be a relatively large but variable fraction of the total air, the computed results would not be suitable, without further adjustment, for selecting an optimum A/F ratio at the carburetor. For high recycle rates at light engine load, the correlated actual A/F ratio, which includes exhaust air, can be as much as 1.3 A/F ratios leaner than the carburetted mixture.

3.0 VEHICLE TESTS

3.1 INTRODUCTION

3.1.1 Purpose

The vehicle test program was undertaken to demonstrate the feasibility of using exhaust gas recycle to reduce nitrogen oxide emission from gasoline powered automotive equipment. It served as a practical application of the engine lab tests discussed previously; it made use of some of the earlier results--for example, the advantage of the Mod. I distributor, which has a more advanced spark curve, when using recycle. Our goal was not only to find how well recycle could suppress NO formation, but also to show that relatively simple equipment would suffice for effecting the recycle. However, it was not our intention to design the exact equipment Detroit would use for such a job. Obviously, details would vary from car to car and maker to maker. Relative manufacturing costs will play a major role in shaping any equipment Detroit uses.

3.1.2 Scope

The use of recycle was tested in two types of cars, one a Chrysler type product fitted with the so-called "clean air package" and the other, a car fitted with air injection into the exhaust manifold. The latter permits operation with a rich mixture and uses added air to burn most of the resulting CO and hydrocarbons in the exhaust. A 1968 Chevrolet with 307 cu. in. engine was selected for the latter and a 1967 Plymouth with 318 cu. in. engine for the former. Operating with recycle requires some changes in the carburetors. These were made only to the extent necessary to demonstrate recycle feasibility since a major carburetor redesign for optimum operation would be too involved for any but the auto makers themselves to do, if and when they adopt recycle.

In addition to establishing the ability of recycle to reduce NO levels, the effect on other performance criteria was evaluated. This includes the effect on fuel economy, on CO and hydrocarbon emission, on "driveability" and car performance and, to a limited extent, on cold engine performance. The effect of recycle on car life, wear, and maintenance requirements is the subject of another program.

3.2 EQUIPMENT AND EXPERIMENTAL PROCEDURES USED

3.2.1 Test Stand Facilities Geared to the Project

Except for a few "driveability" tests carried out on our MAD (mileage accumulation dynamometer) units and on the road, the testing has been done on Clayton Dynamometer stands. Most testing was on the No. 1 stand at Esso; this is fitted with acceleration weights equivalent to a 4,000 lb. car. A few tests were made on the No. 2 stand and on a stand of a major auto maker in Detroit; these tests were made using both 4,000 and 4,500 lb. equivalent weights. All stands were equipped with recording infrared analysers for hydrocarbons, CO, CO_2 and NO, as well as recording O_2 analysers and Flame Ionization Detector type total hydrocarbon analysers. All stands were connected to a special type PDP-8S Digital Equipment Company computer furnished and programmed by Beckmann to accept the output from the CO, CO_2 and hydrocarbon analysers and compute the corrected and weighted averages for the so-called "California Cycle" as prescribed in the Federal Register, Vol. 33, No. 108, June 4, 1968. The computer at Esso has been programmed to accept, store and print out data from two stands simultaneously; when using only one stand, the NO analyser output from it can be fed in to the computer (after loading its calibration curve) in place of the hydrocarbon analyser output from the other stand. Thus we obtain calculation and printout of the NO results as well. In Detroit, the NO data were calculated by hand. The computer furnished to Esso was plagued with defective transistors, etc., for the first six months. As a consequence, many early tests on the Plymouth used bag samples for the California as well as the USPHS cyclic tests. A few California cycles were calculated by hand. Many steady state ("cruise") type tests were also run, generally to check results from the earlier engine lab tests, or to get actual values for air/fuel ratio.

The No. 1 stand is also provided with an eight pen recorder and assorted transducers to record such items as engine speed, spark advance, air flow rate (to carburetor), recycle rate, recycle pressure, recycle temperature, intake manifold pressure and fuel rate. The latter item, however, proved quite inaccurate when used with an extremely small turbine type meter; it was abandoned in favor of direct weighing methods described below. The air flow rate is measured as a ΔP across a 500 CFM Meriam laminar flow meter in the air stream to the carburetor; a large air filter protects the small tubes in this flow meter from fouling. Recycle rate is measured with a one-inch size turbine meter (Potter Aero. Co.) in the recycle line. This generally held its linear calibration within a very few percent--at least until its bearings became fouled and worn out; the bearings are a dry lubricated "sealed" type so this has happened only twice in about eight months of use. (The condition of the bearings can be checked by removing the flow meter from the recycle line, gently blowing by mouth at the inlet and watching the fan blades to see that they spin easily and coast for a few seconds afterward. Generally, the trace on the recorder will show its condition; if it records properly the small amount of recycle at the 30 MPH cruise portion of the cycle and takes a few seconds to coast to zero after the recycle valve shuts off at the start of the deceleration, the flow meter is in good condition.)

Fuel consumption in cyclic operations is measured by feeding the carburetor from a weighed quart can of fuel for exactly three cycles. Either a weighed bottle or a 200 cc burette is used to measure fuel rate in steady state (cruise) operations; an electric stopwatch accurately measures the time period supplied by the measured amount of fuel. Accuracy better than 0.5% is easily attained for fuel rate.

Figures 3.1 and 3.2 show the Plymouth test car on this Clayton #1 stand. The computer is in the right foreground with the Beckman analyzers and recorder beyond it. The car's rear wheels are on the dynamometer rolls. In the left foreground is the radiator water cooler. Behind this is the transducer panel and recorder for the car operating data. A large cooling fan sits in front of the car.

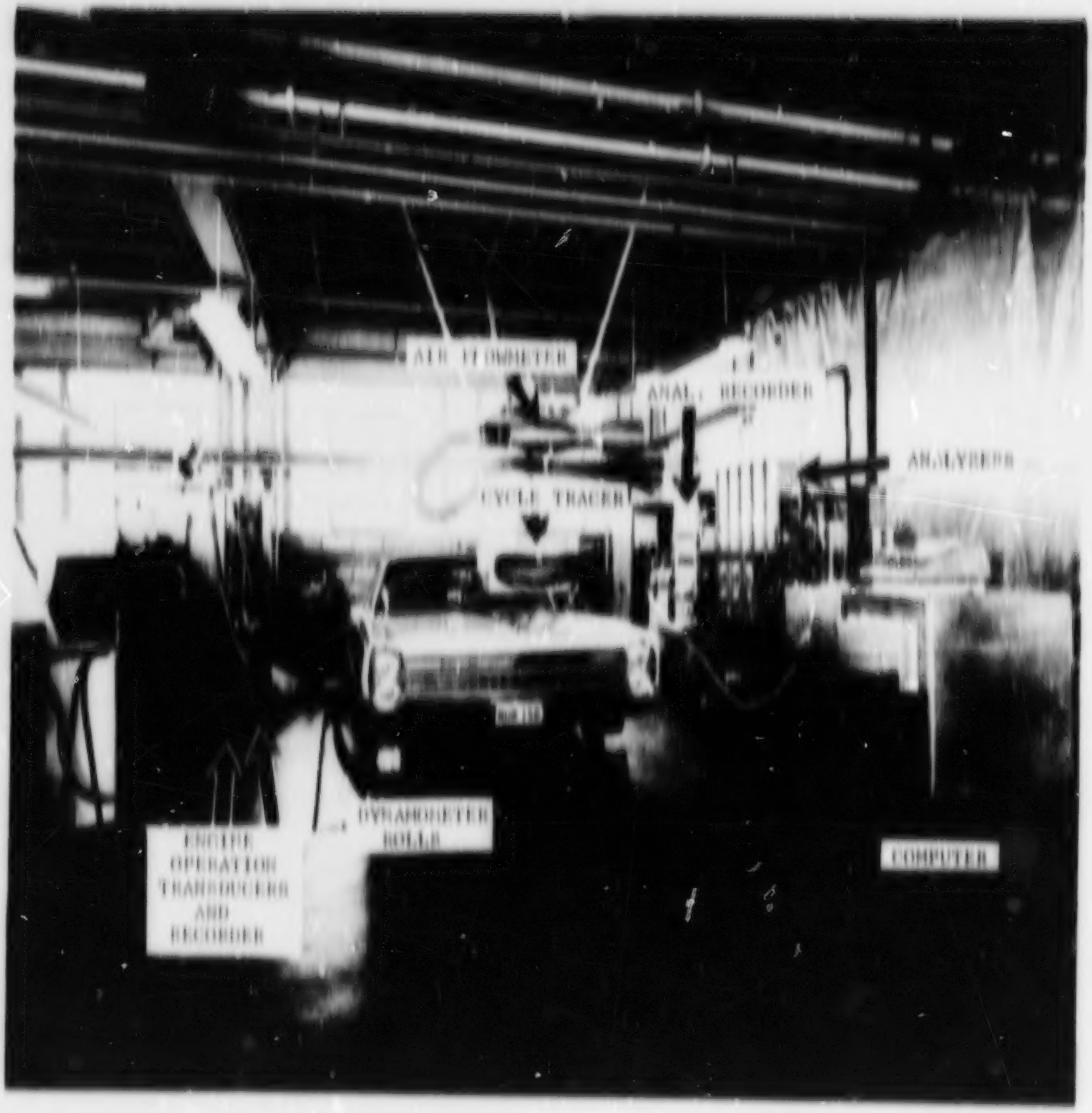
In order to get the best comparisons possible of operations with and without recycle, *"back-to-back" hot operations* were made. These might be a standard 7 cycle California test with computer workup (or bag analyses) of the result. Thus recycle might be used in the first four cycles (calculated as "cold engine" results in the normal California test when started cold) and the recycle turned off for the last three cycles. Thus the two computer averages (cycles 1-4 for cold and 6-7 for hot) really represent results *with* recycle (1-4) and *without* recycle (6-7). Obviously the reverse order of recycling could be used but in any case a comparison is obtained for the hot operations over such a short period of time that external variables (humidity, etc.) would have little chance to change.

Figure 3.3 shows a typical computer print-out for the normal cold-start California Cyclic test. Figure 3.4 is a similar print-out for a hot-start California Cyclic test, back-to-back with and without recycle.

Figure 3.5 is a typical recorder chart of engine operating variables for a period covering somewhat more than one California cycle. Figure 3.6 is the corresponding recorder chart for the exhaust gas analysis; the drastic decrease in NO due to the use of recycle in Cycle 5 is evident.

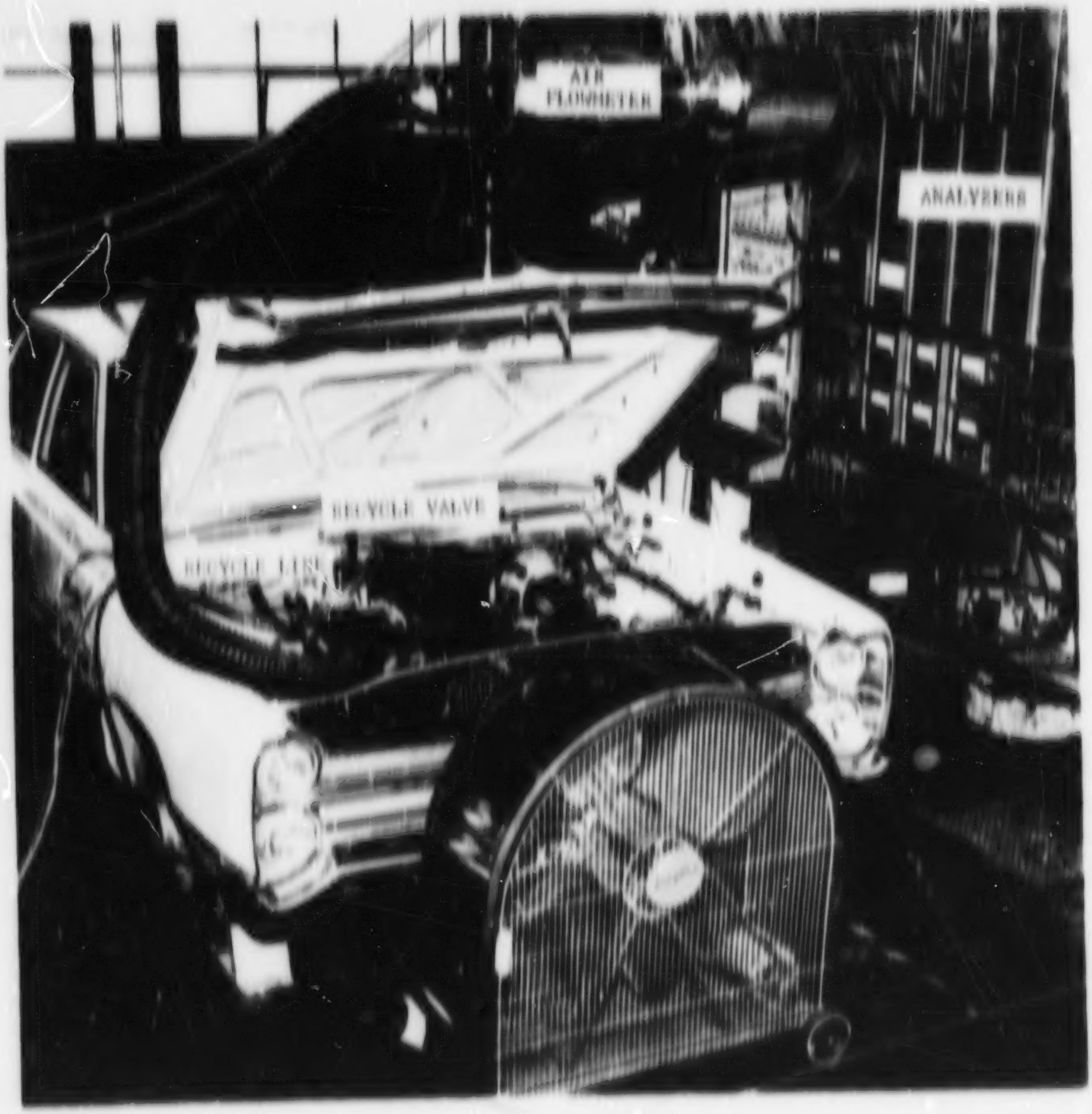
To assist the operator in following the prescribed speed changes over the 137 second California cycle, a *Cycle Tracer* made from a relatively large X-Y plotter showing speed vs. time is mounted in front of the windshield, as shown in Figure 3.7. The traveling "pen-holder" carries a stylus; the path for it to follow is engraved on a bakelite board. The California cycle covers 8 x 14 inches on this board. Until recently the operator signaled the computer (by a push-button) at each of the speed change points defining the 7 "modes" of this cycle. Now, an automatic switching device has been installed in the plotter to signal these points more accurately and to allow the operator to concentrate on driving the car to match the desired cycle curve.

FIGURE 3.1



CLAYTON DYNAMOMETER STAND # 1

FIGURE 3.2



CLAYTON DYNAMOMETER STAND # 1

FIGURE [illegible]

EXHAUST EMISSION TEST REPORT

DATE [illegible] CAR [illegible] MAKE [illegible]

TEST [illegible]

[illegible]

SCHEDULE SUMMARY

[illegible]

FIGURE 3.5

EXHAUST EMISSION TEST REPORT

DATE 11/18/68 CAR 813 MAKE PLYMOUTH

TEST [illegible] CALIFORNIA CYCLES WITH AND WITHOUT RECYCLE EXHAUSTING THROUGH BLOWER WITH BLOWER TURNED OFF. 13/32" ORIFICE-- MOD #1 DIST. USING 4500 LB. INERTIA WT.

CYCLE	MODE	VALUES HC	CO	NO	CO2	CF	CORRECTED HC	CO	NO	WEIGHTED HC	CO	NO	
1	1	310	1.80	120	13.70	0.990	303	1.78	116	8	0.03	3	WITHOUT RECYCLE
	2	320	0.98	1800	13.68	1.060	371	1.01	1250	63	0.14	270	
	3	262	0.47	1710	13.38	1.067	276	0.50	1830	30	0.05	201	
	4	360	1.35	530	13.10	1.030	369	1.38	505	35	0.09	30	
	5	300	1.72	300	13.69	0.975	314	1.60	211	10	0.06	10	
	6	270	0.73	2600	13.46	1.037	209	0.77	2088	122	0.33	1030	
	7	1,000	1.57	530	11.03	1.001	1050	1.61	488	37	0.02	13	
2	1	300	1.30	150	13.62	0.961	278	1.32	145	11	0.05	6	
	2	380	1.03	2030	13.38	1.030	371	1.05	2092	75	0.13	310	
	3	720	0.42	1530	13.58	1.170	830	0.50	1567	45	0.36	191	
	4	250	1.47	810	13.10	1.014	600	1.57	810	27	0.03	33	
	5	290	1.75	280	13.70	0.370	130	1.62	215	11	0.10	10	
	6	301	0.33	2593	13.52	1.060	318	0.76	2750	121	0.33	1029	
	7	1,130	1.57	890	11.07	1.033	1030	1.77	900	54	0.03	11	
3	1	300	1.52	185	13.70	0.976	170	1.60	156	11	0.03	6	
	2	300	1.07	2050	13.50	1.063	325	1.02	2081	73	0.14	302	
	3	298	0.47	1740	13.85	1.083	308	0.50	1850	36	0.03	213	
	4	380	1.80	510	13.00	0.388	388	1.58	475	35	0.09	33	
	5	290	1.76	200	13.50	0.371	230	1.70	195	11	0.06	9	
	6	290	0.61	2530	13.50	1.086	300	0.63	2570	127	0.35	1015	
	7	1,700	1.75	410	11.05	1.050	1043	1.77	390	36	0.05	12	
4	1	230	1.31	160	13.73	0.977	300	1.21	150	11	0.06	6	
	2	320	1.10	2000	13.33	1.030	320	1.13	2101	52	0.07	312	
	3	280	0.33	1390	13.72	1.031	295	0.37	1430	35	0.07	170	
	4	380	1.33	550	13.10	1.033	650	1.43	598	37	0.07	33	
	5	330	1.70	230	13.73	0.370	230	1.62	225	11	0.06	10	
	6	300	0.33	2400	13.38	1.053	305	0.76	2333	131	0.33	1033	
	7	1,230	1.55	800	11.05	1.067	1256	1.50	450	56	0.03	13	
101	1	320	1.33	140	13.73	0.369	260	1.30	140	10	0.06	5	
	2	352	1.05	2028	13.50	1.031	314	1.08	2075	72	0.14	303	
	3	271	0.43	1580	13.80	1.085	285	0.50	1662	33	0.06	193	
	4	340	1.39	570	13.10	1.023	362	1.53	556	37	0.09	32	
	5	290	1.75	263	13.67	0.976	321	1.68	217	11	0.08	10	
	6	250	0.70	2560	13.51	1.050	300	0.81	2510	127	0.37	1022	
	7	1,110	1.65	520	11.05	1.080	1055	1.70	500	56	0.03	13	
					AVER	1.027	580	1.65	1100	381	0.97	[illegible]	
6	1	290	1.56	140	13.60	0.977	282	1.10	188	11	0.03	6	WITH AUTO. RECYCLE 13/32" ORIFICE
	2	350	1.17	1000	13.53	1.000	350	1.17	1000	65	0.17	252	
	3	320	1.15	370	13.35	0.990	305	1.14	360	36	0.13	56	
	4	600	1.75	210	12.90	0.933	565	1.70	207	39	0.13	10	
	5	290	1.58	210	13.80	0.973	260	1.56	205	11	0.07	10	
	6	310	0.72	1250	13.35	1.006	318	0.72	1255	132	0.33	531	
	7	1,000	1.64	225	10.95	1.085	1090	1.81	250	57	0.06	4	
7	1	290	1.26	150	13.30	0.356	288	1.21	146	10	0.05	6	
	2	310	0.98	1070	13.98	1.016	319	0.91	1011	72	0.20	253	
	3	300	1.11	380	13.96	0.995	318	1.10	380	37	0.13	54	
	4	690	1.60	210	13.10	0.922	675	1.58	210	34	0.09	11	
	5	270	1.36	200	13.60	0.392	265	1.35	208	11	0.07	10	
	6	310	0.75	1300	13.35	1.030	328	0.76	1410	155	0.36	572	
	7	1,030	1.59	300	10.98	1.107	1014	1.75	278	58	0.08	5	
101	1	270	1.60	150	13.80	0.991	169	1.37	150	11	0.03	6	
	2	325	1.01	1035	13.90	1.005	326	1.04	1032	69	0.09	253	
	3	352	1.13	365	13.97	0.953	300	1.10	361	36	0.13	55	
	4	630	1.67	210	13.15	0.958	630	1.62	202	36	0.10	11	
	5	280	1.32	230	13.70	0.372	255	1.35	205	11	0.07	10	
	6	310	0.74	1258	13.31	1.023	318	0.75	1400	144	0.34	551	
	7	1,015	1.62	310	10.90	1.101	1098	1.76	258	58	0.07	5	
					AVER	1.011	583	1.36	510	382	0.93	994	

SCHEDULE SUMMARY

HC.PPM	%CO	NO.PPM	CF	
381	0.97	[illegible]	1.027	WITHOUT RECYCLE
382	0.95	994	1.011	WITH RECYCLE (13/32" critical auto)

FIGURE 3.5

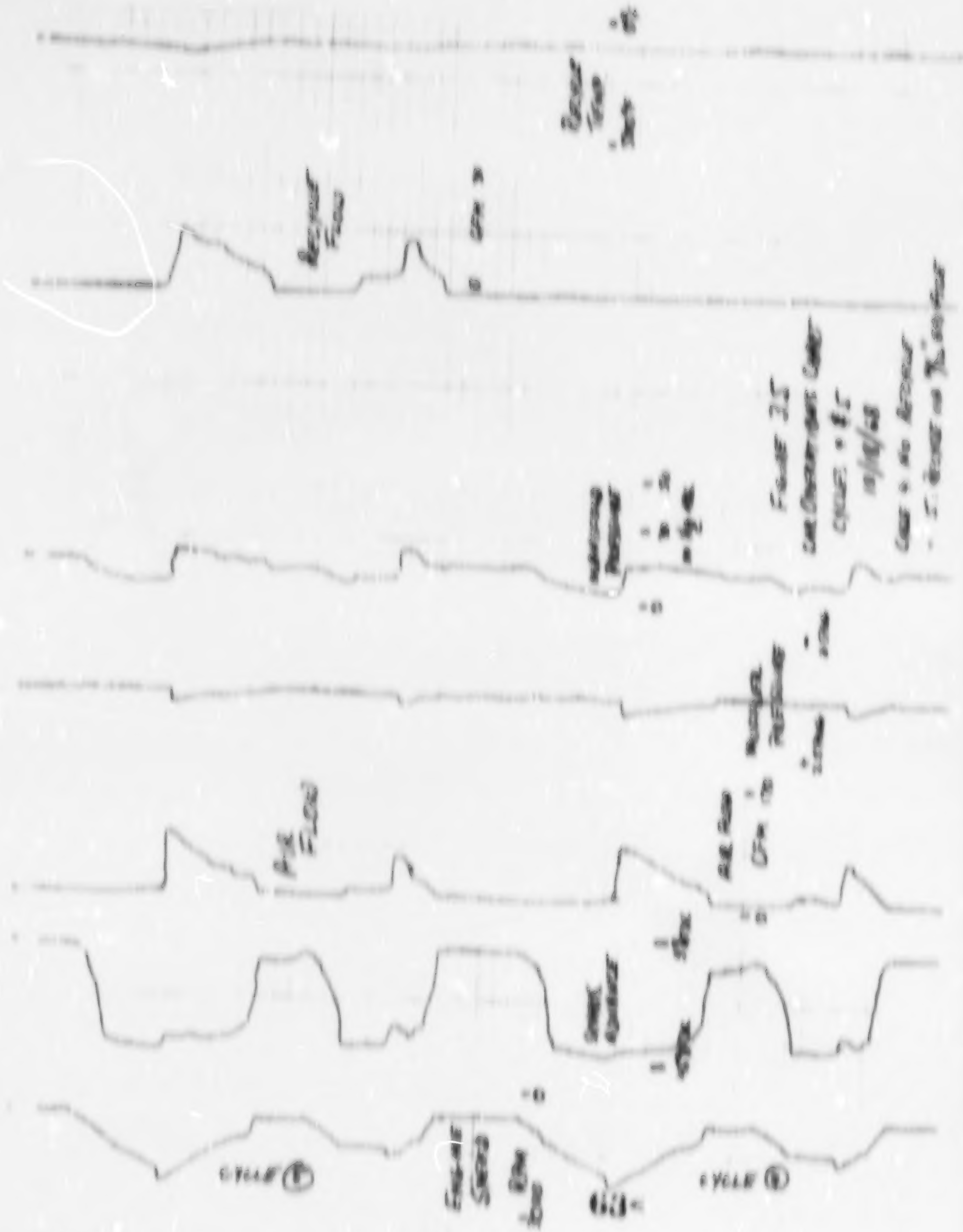


FIGURE 3.6

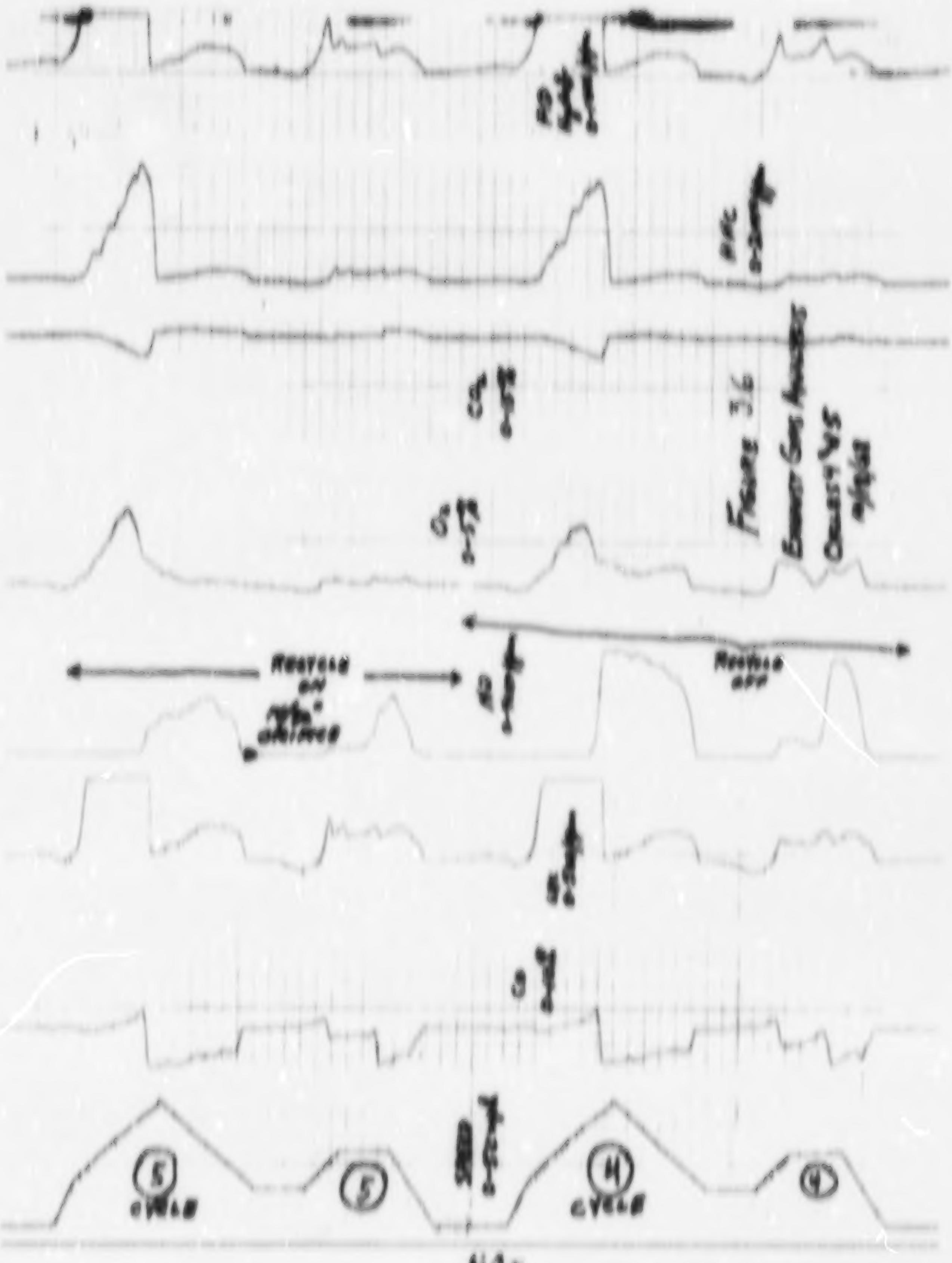
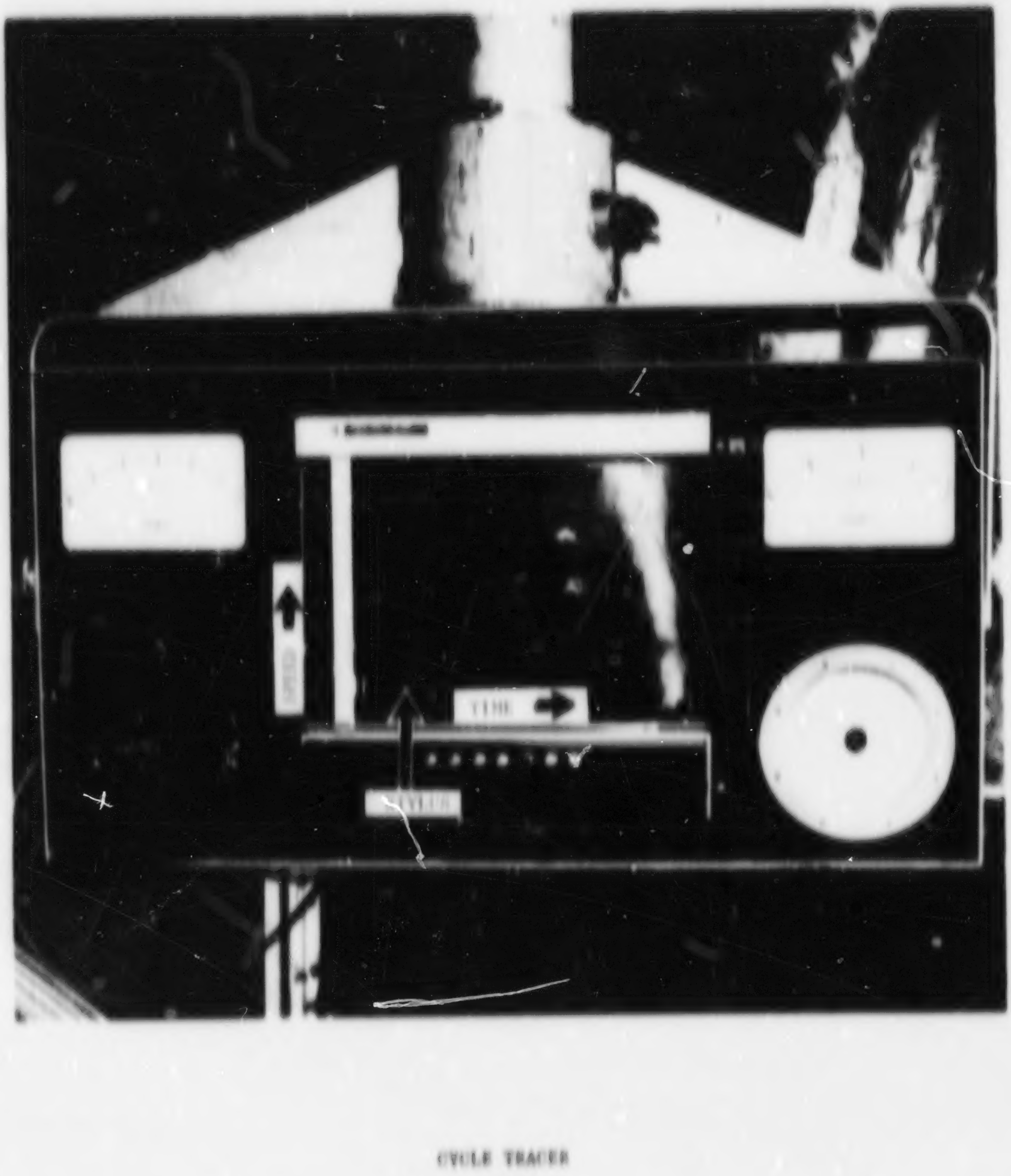


Figure 3.6
Exhaust Gas Analysis
Cycles 4 & 5
SPEED
5
CYCLE
5
4
CYCLE
4

FIGURE 3.7



CYCLE TRACER

3.2.2 Recycle System Made Simple

For reliable, reproducible operation with exhaust gas recycle, it is desirable to keep the amount of recycle a more or less constant proportion of the air flow into the engine. Since the volume of exhaust gas is a direct function of this same air flow, this is tantamount to saying that the recycle should be proportional to the flow of exhaust through the muffler, at least over ranges of appreciable power output where NO production becomes serious. Providing this proportioning was a major problem to be solved. The engine lab tests had shown that the original valve furnished to Esso did not work satisfactorily. Devices under development in parallel Esso programs were made available to this study.

Two different vacuum-operated proportioning valves were tried, one proposed by a Detroit consultant and one designed by our own Mechanical Department. The latter was fitted with a square-root cam to match the flow characteristic of the muffler. (With turbulent flow of gas through the orifices in the muffler, flow rate would be approximately proportional to the square-root of the pressure drop.) The other valve attempted to use engine vacuum balanced by a pair of springs and a lever arm to proportion the recycle; since vacuum was a function of engine speed, load and throttle position it was not too good a measure of gas flow through the engine. Both valves had poor reproducibility due to their involved mechanical construction, friction, etc. After several tests, we abandoned both valves in favor of a simpler, more direct approach that had been developed in a parallel program.

Theoretically, recycle gas tapped off the tail pipe upstream of the muffler and passed through an orifice to a point where the pressure is effectively the same as that downstream of the muffler should be in a fixed ratio to the flow through the muffler; this results because turbulent flow through the recycle orifice and through the tubing is nearly a square-root function of the pressure drop, as is the flow through the orifices in the muffler. Since all components of the system have similar relations between flow and pressure drop, the flow ratio should be more or less constant. As shown later, this has been the case.

In order to keep the recycle flow proportional only to the muffler (and tail pipe) back pressure, the recycle cannot be introduced directly into the intake manifold; the wide variations in vacuum, an order of magnitude greater than the muffler back pressure, would play havoc with any attempt to control the recycle flow. On the other hand, if the recycle were introduced upstream of the carburetor's venturi any variation in recycle would play havoc with the carburetor's control of air/fuel ratio. Thus, it becomes necessary to introduce the recycle gas downstream of the venturi but ahead of the throttle plate. This requires a remodeling of the carburetor when the throttle is integral with the carburetor body.

In order to introduce the recycle gas at this point, a special plate about 3/4 inch thick was made up to fit between the carburetor and throttle plate. It was provided with an opening at the side to connect the recycle line. All vacuum and fuel passages between the carburetor body and throttle plate housing were maintained by isolated passages through the plate. The recycle opening was split equally between the two barrels of the carburetor to maintain uniform distribution. To permit insertion of this plate, several of the linkages on the carburetor had to be lengthened by an amount at least equal to the thickness of this plate. Figure 3.8 is a shop drawing of this plate for the Plymouth. Figure 3.9 is a photograph of it. A similar plate was used in the Chevrolet.

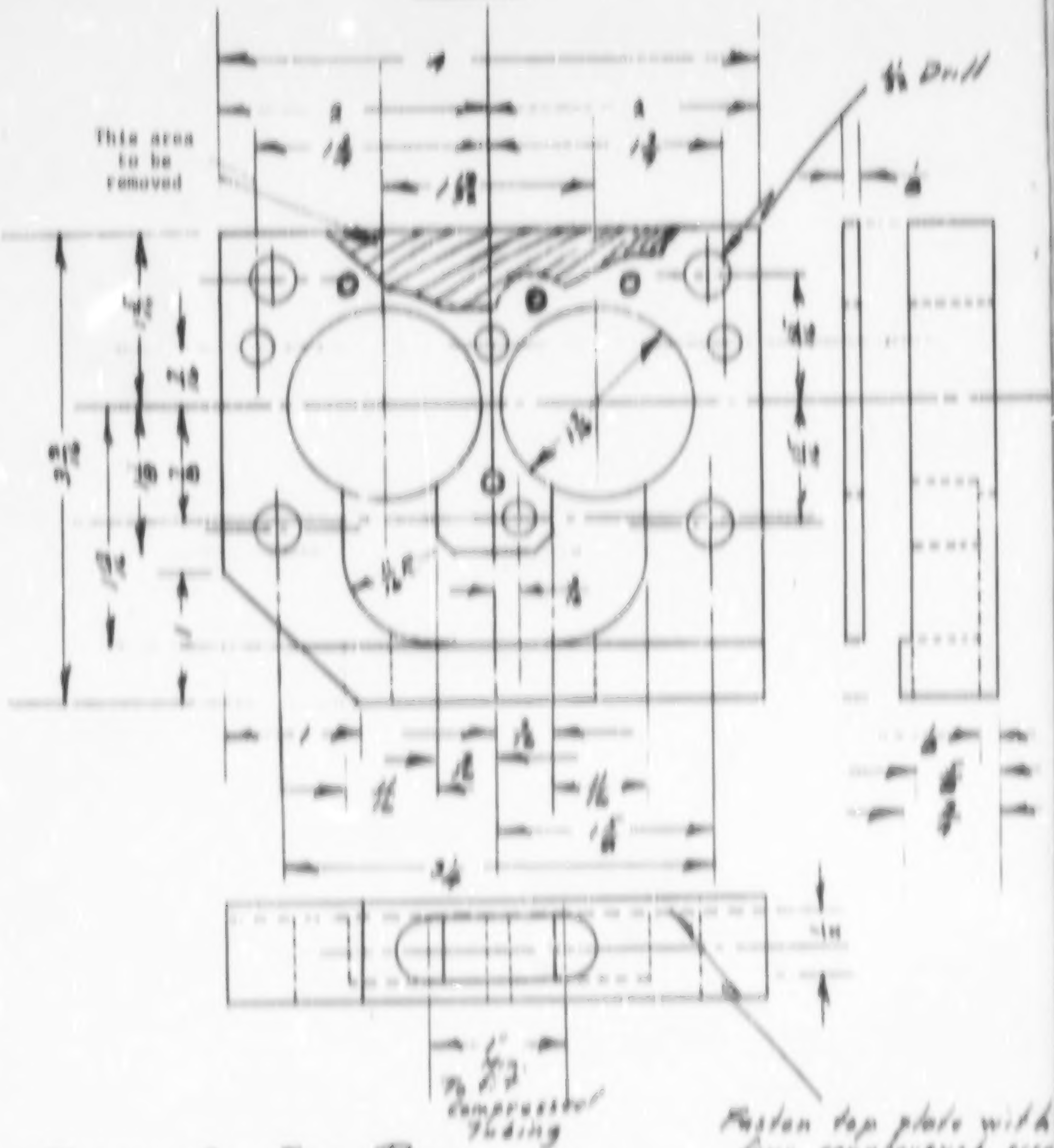
Figure 3.10 is a schematic flow plan for this simple recycle system as installed in the Plymouth. To provide more cooling of the recycle gas before it gets near the carburetor, several extra feet of tubing (some of it finned) are used in the recycle line. In addition, a large hole was cut in the vertical plate beside the radiator to permit a good blast of cooling air past the recycle tube. The recycle line maintains a continuous slope back to the tail pipe so any moisture condensed will drain back to the tail pipe and muffler. The cooled recycle gas next passes through the flow limiting orifice contained in the flange of the ball-type shutoff valve, through this vacuum operated valve, through the turbine type flow meter, past a thermocouple and into the recycle plate in the carburetor. To provide maximum versatility in this research project, the OFF/ON recycle valve is controlled by electric switches inside the car and on the accelerator linkage. These switches control a 3 way solenoid valve which either feeds high vacuum (from the brake reservoir) or bleeds atmospheric air into the operating diaphragm of the recycle valve. The switches on the accelerator linkage can be adjusted to turn off the recycle during periods of idle or wide-open throttle; this has been designated "automatic" operation. The switches inside permit the operator to select this "automatic" operation, or no recycle, or continuous recycle. This is very handy for comparing operation on the road with and without recycle. The flowmeter, made by Potter Aeronautical Company in Union, New Jersey, is a one-inch size Model 1-50327-G fitted with sealed ball bearings.

Figure 3.11 is a photograph of this recycle system as applied to the Plymouth car; the vertical plate beside the carburetor is the mount for the two switches operated at idle and wide open throttle. In Figure 3.11, the air cleaner has been removed to better show the recycle flow meter and other items.

The recycle system for the Chevrolet was similar to the Plymouth system just described. The Chevrolet muffler is nearer the rear of the car so the recycle exhaust line under the car was long enough for cooling and no extra tubing was installed under the hood. As shown in Figure 3.12, the recycle line comes up directly in front of the fire wall through the OFF/ON valve, through the turbine type Potter flowmeter, past a thermocouple and into the plate inserted in

.438 sq in inlet

FIGURE 3.8



Recycle Gas Inlet Plate

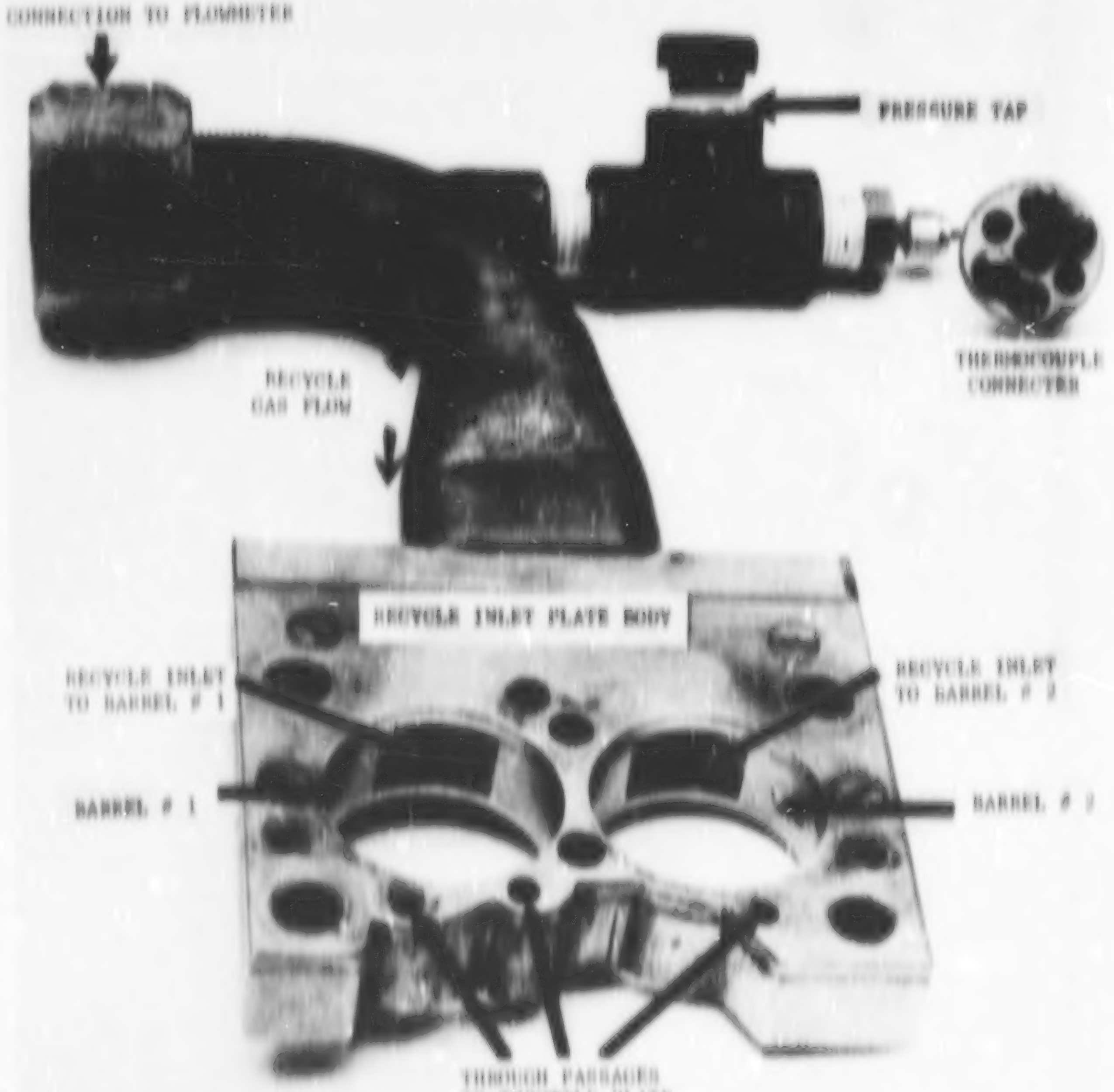
Material - 304 S.S.

Adapter for Stromberg Model W.W.
Above Throttle

Fasten top plate with four countersunk screws and final seal with Sealite gasket compound after welding on inlet tube.

5/3/68

FIGURE 3.9



RECYCLE GAS INLET PLATE

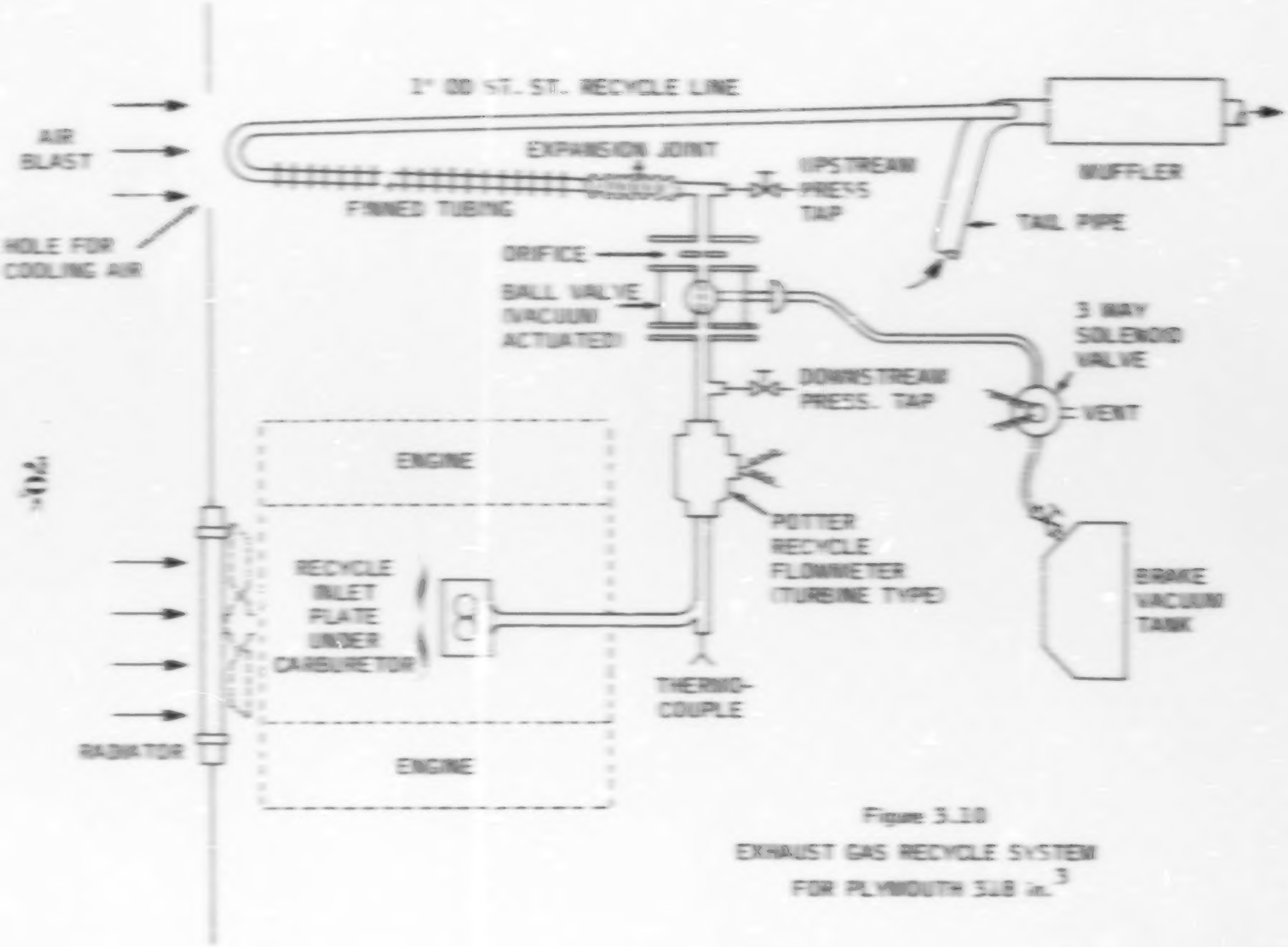
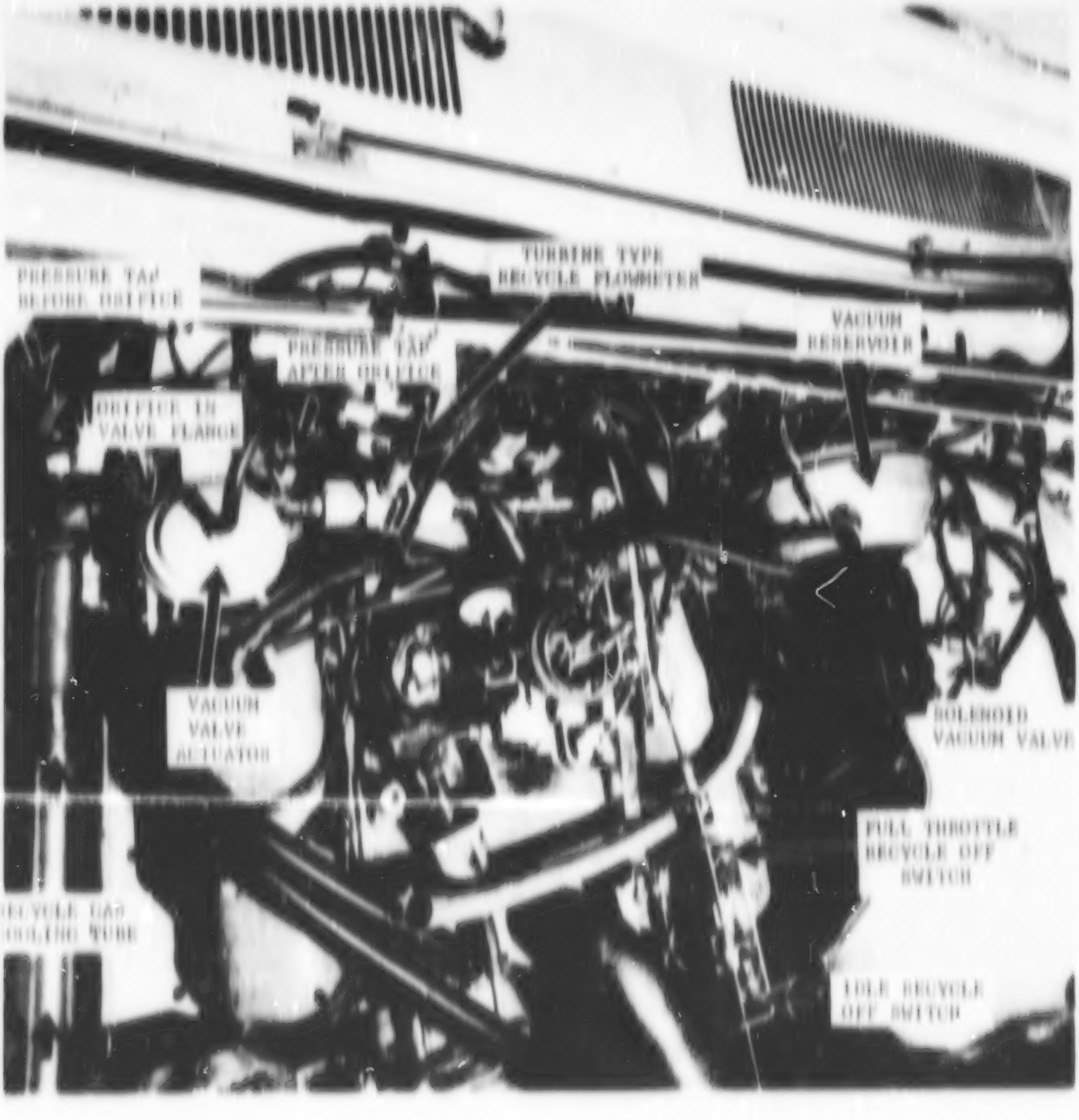


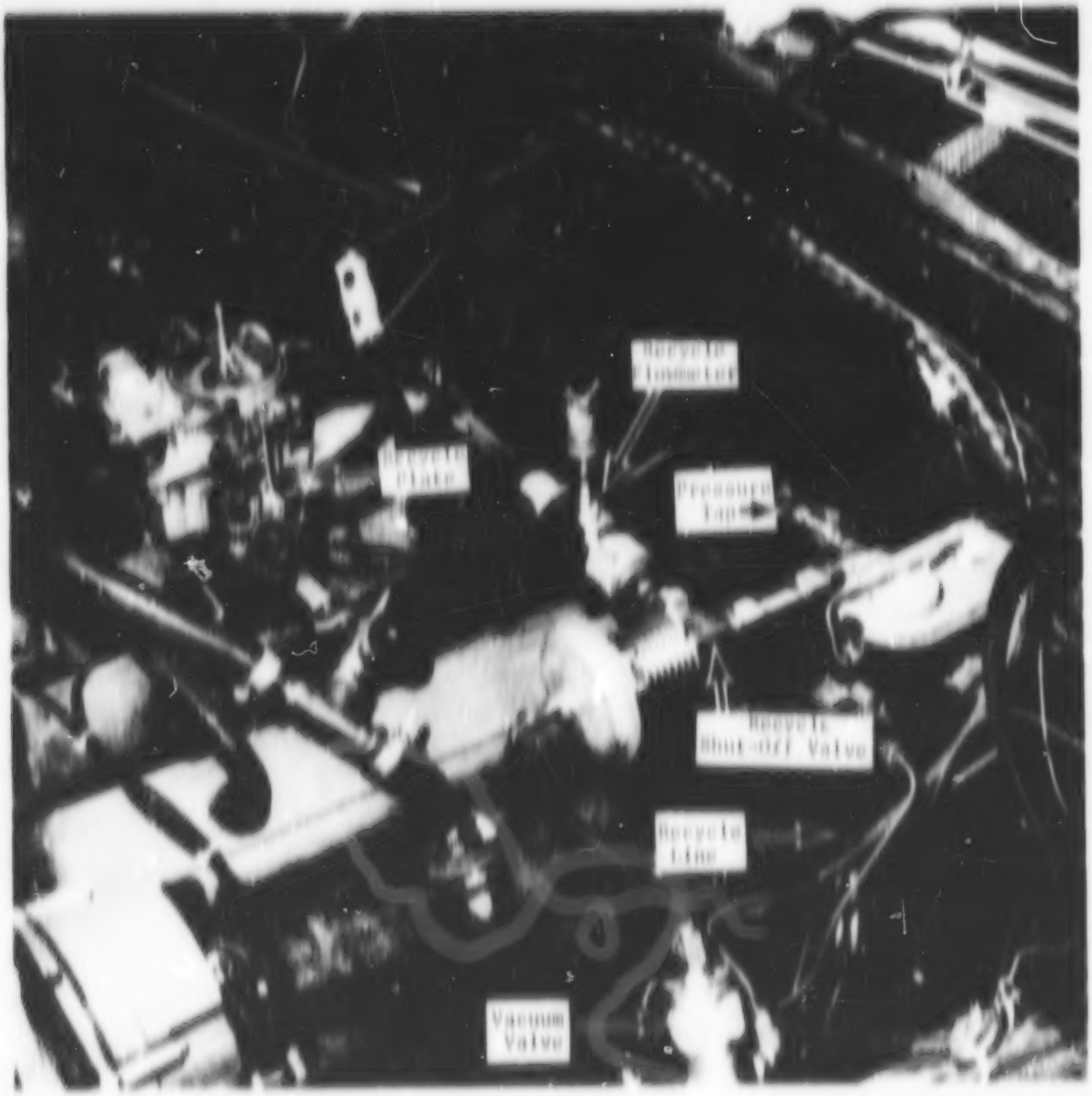
Figure 3.10
EXHAUST GAS RECYCLE SYSTEM
FOR PLYMOUTH 318 in.^{3}

FIGURE 3.11



PLYMOUTH RECYCLE SYSTEM

FIGURE 3.12



CHEVROLET RECYCLE SYSTEM

the carburetor. The valve is not the rotating-ball type used in the Plymouth, which sometimes fouled up enough to stick or hang up. Instead, a bellows-sealed plug type valve was built from a 3/4" Swagelok Tee. The plug was held closed by a spring and opened by a vacuum diaphragm. The spring used happened not to be quite strong enough to keep the valve completely closed against the back pressure developed by the muffler (over 2 psig) at wide-open throttle at speeds above 50 mph; at this condition a few percent recycle did leak through even when supposedly closed. It occurred only at the end of wide-open acceleration tests and so had no effect on the emission testing and normal driveability tests. Normal recycle was controlled by the fixed orifice selected for insertion in the inlet connection to the valve.

Table 3.1 below shows the orifice sizes used for controlling recycle rate and the rate expected from each, expressed as % based on air flow rate. The largest sizes are approaching the hole size in the shutoff valve so have less control over the rate. Back pressure from the muffler is such that at the end of the 15-30 MPH acceleration in the California cycle, it reaches a peak of 0.6-0.8 psig with the Plymouth and 1.4-1.7 psig with the Chevrolet. The rates shown are average values and may vary 1 or 2 actual % on air from test to test, mostly due to variations in the recycle gas temperature since volume must be corrected to air temperature. Two values are shown for the Chevrolet since the air injection into the exhaust causes considerable air to be recycled. This must be considered as part of the air supply to the engine rather than as recycle. The "Total" column includes this air, the "Inert" does not. There is so little O_2 in the Plymouth exhaust that no such distinction has been made.

Table 3.1

Recycle Rate

Orifice Size Vs. Vol. % on Air Rate

Orifice Diameter (Inches)	Plymouth Rate (Total)	Chevrolet Rate	
		Total	Inert
9/32	7	11.5	8.2
10/32		14	9.8
11/32	9.5		
12/32		19.2	13.1
13/32	12.5	22	15.7
14/32	14.5	25.2	17.3
15/32	17	28.4	19.1
16/32		29.4	20.2
17/32	24.5		

3.2.3 Carburetor Modifications

In addition to the recycle plate mentioned earlier, and its attendant linkage changes, other modifications have been necessary to prevent the use of recycle changing the air/fuel mixture too drastically. The Plymouth carburetor as an example has in addition to the accelerator pump:

2 - main fuel jets
2 - idle jets
6 - transfer jets (3 at edge of each throttle plate)
4 - power jets

The Chevrolet's Rochester carburetor is similar except it has only one power jet in each barrel instead of two. When recycle is used, power decreases for a given throttle opening so that a larger throttle opening is required to maintain speed. This means vacuum is lower for the same speed, which in turn will allow the power valve in the carburetor to open sooner. Thus, recycle tends to cause richer mixtures and more CO and HC. We had not the facilities nor time to design a new carburetor for use with recycle as Detroit certainly would do. The transfer jets especially would be hard to change since they are small holes in the wall of the carburetor throat; yet they are certain to feed more fuel and less air as the throttle opens farther past them when recycle is used.

To prevent excessive enrichment during accelerations (as shown by high CO emission) it was necessary to readjust the spring tension on the Plymouth power valves so that the first stage would not open until vacuum had fallen below 10" mercury. Spring tension on the second stage was then increased to permit it to still open when vacuum drops below 5" mercury. The normal settings as furnished originally are for operation at about 13" and 4.5" mercury, which will not allow the second (large) power valve jet to open during the California cycle when not recycling. For the same reason, the spring on the Chevrolet power valve had to be shortened to prevent the power valve from opening during a California cycle when recycling.

3.2.4 Distributor Modifications

Some tests with the Plymouth were made with the original ("manufacturer's") distributor but most were made with the "Mod. 1" distributor as used in the earlier engine tests. The difference in their timing curves can be seen by comparing Figures 3.13 and 3.14. The "Mod. 1" curves have more spark advance at most points and the vacuum advance operates over a wider range of vacuum. The Mod. 1 distributor was selected because the earlier engine tests had indicated that it would permit recycling with little or no loss in fuel economy and no increase in CO or HC emission.

No such modified distributor was developed for the Chevrolet. Instead, a few tests were made with the spark advanced 5°. The spark advance curve for the distributor supplied with the Chevrolet is shown in Figure 3.15.

FIGURE 3.11

SPARK SETTING FOR PLYMOUTH

Based on MID-PT of Manufacturers'
Factory Distributor Curves

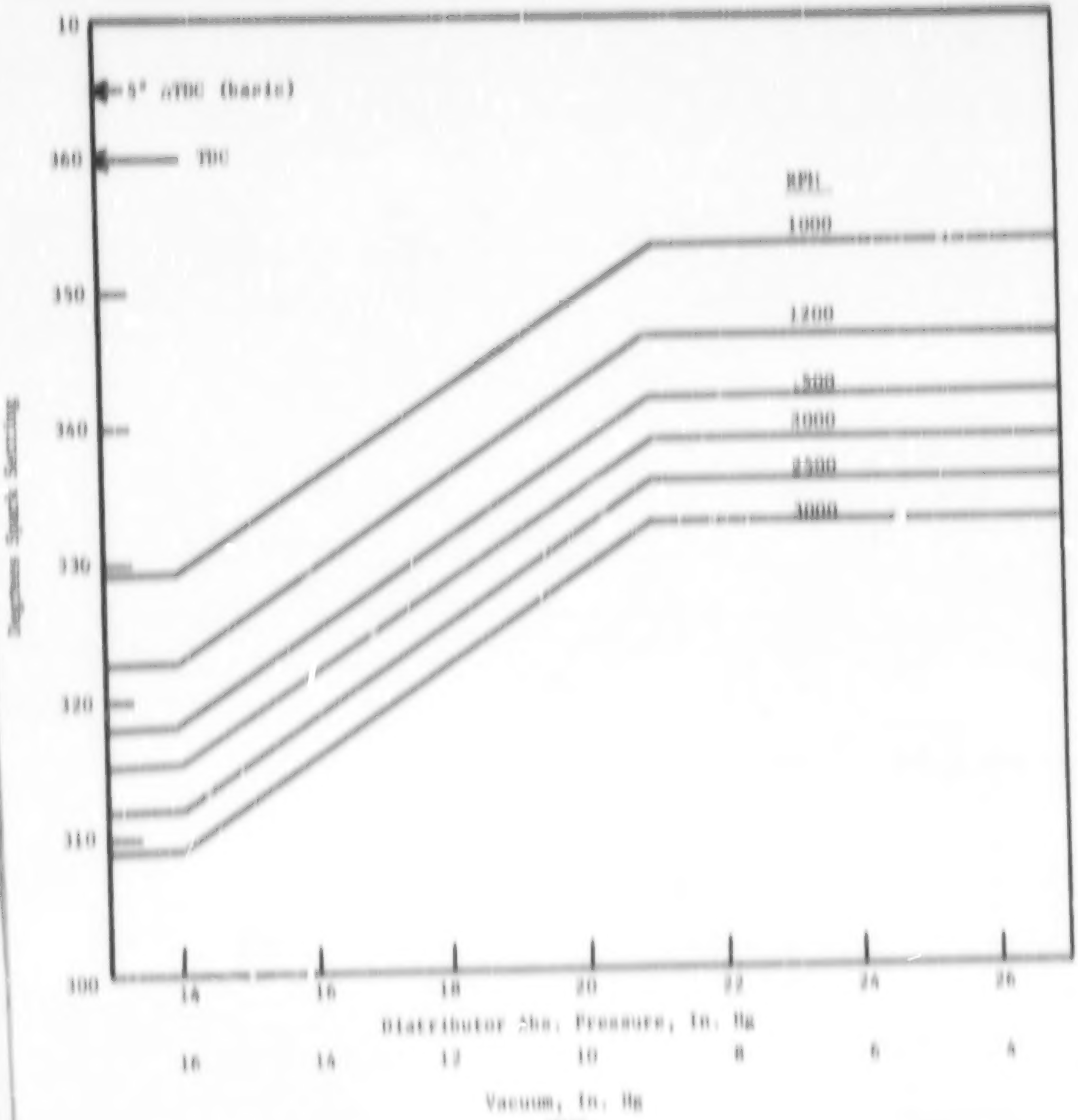


FIGURE 3.16

SPARK SETTING FOR PLYMOUTH

Based on Chrysler Data
for MOD-1 Distributor

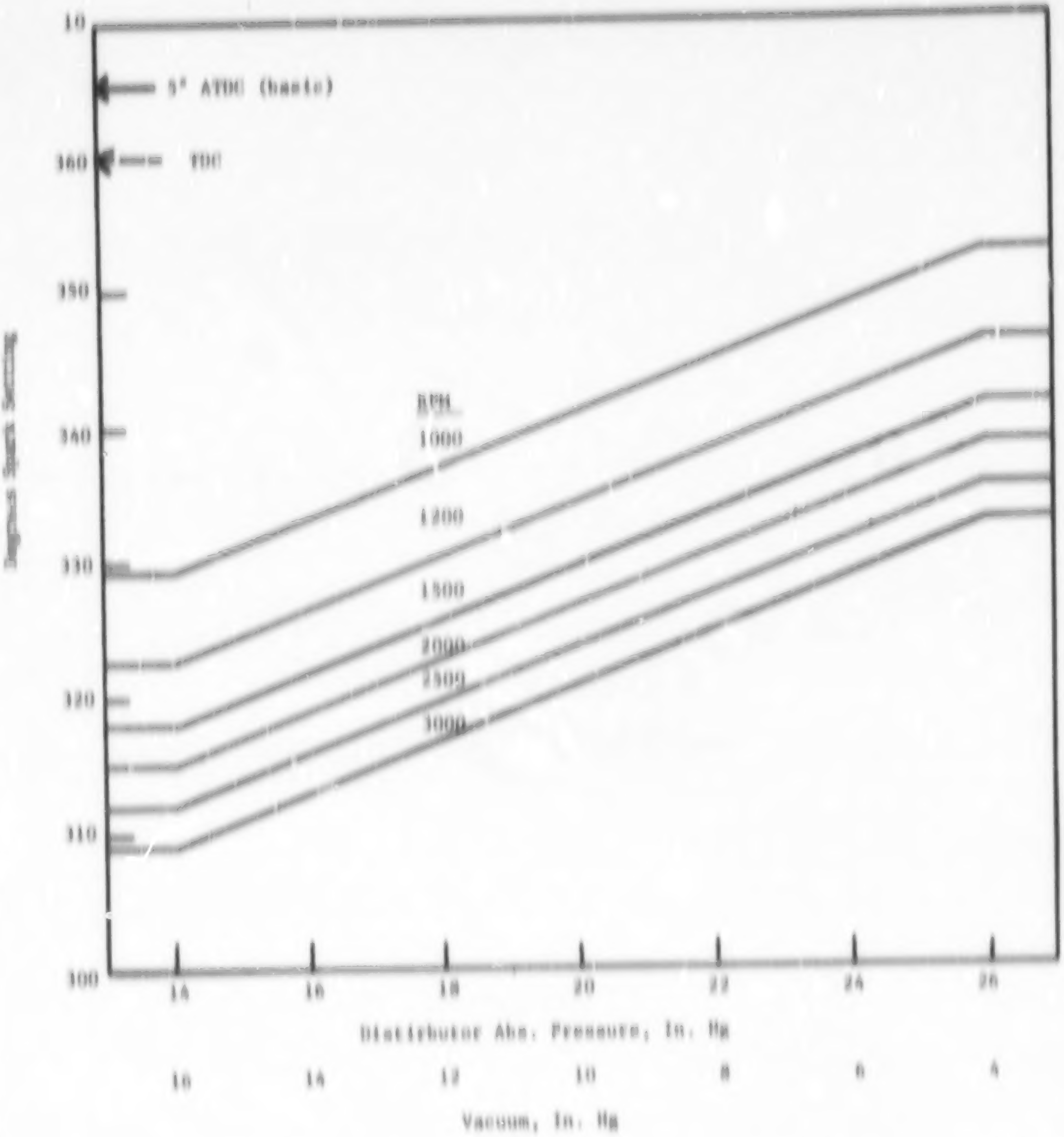
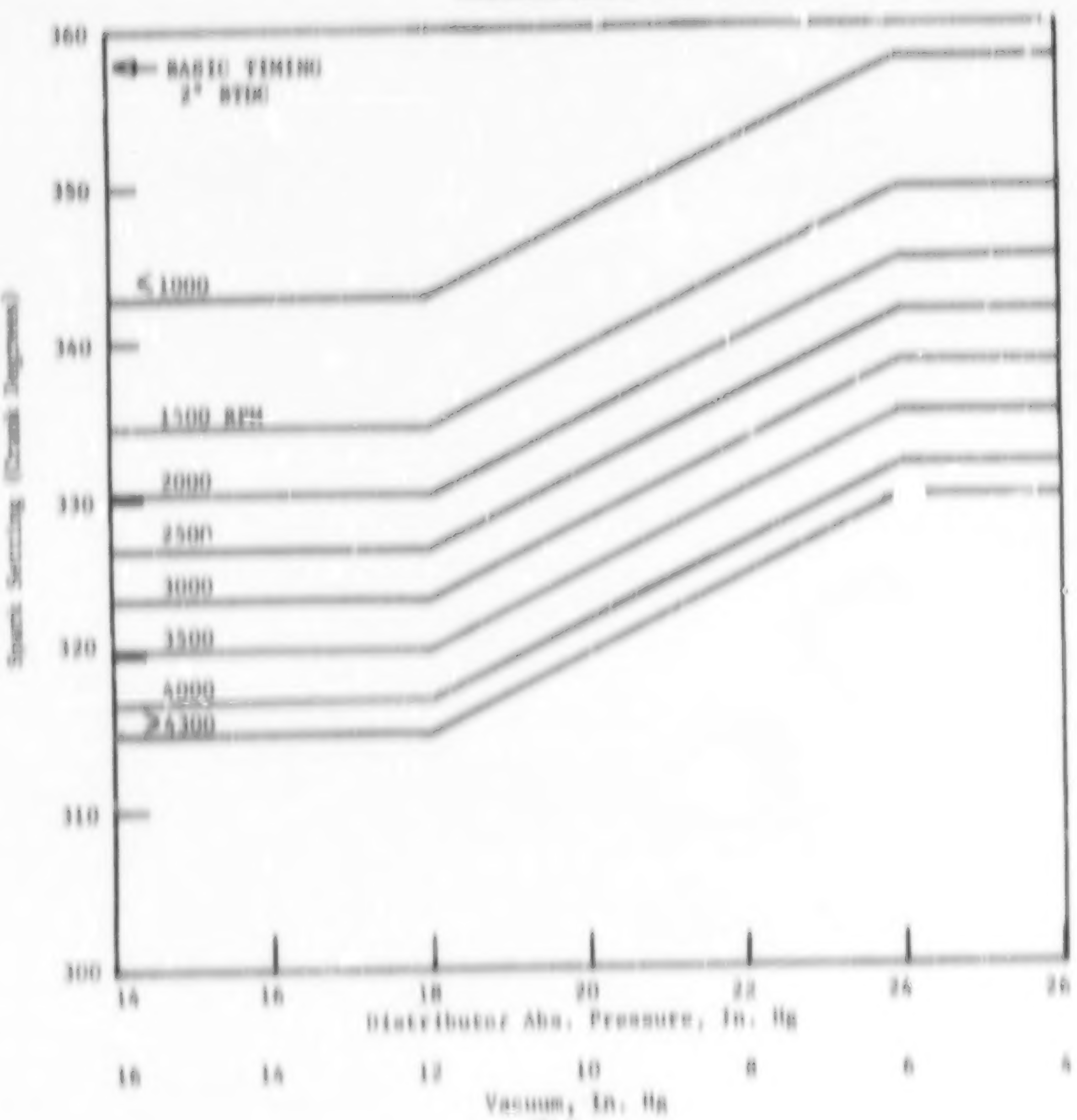


FIGURE 3.15

SPARK SETTING FOR CHEVROLET



3.3 RESULTS AND DISCUSSION

3.3.1 Operability of the Direct Recycle System is Good

Performance of this simple system has been good. The recycle rate is in close proportion to the air flow rate. This can be seen by comparing the general shape of the two curves for a California cycle as shown in Figure 3.5. There is a little lag in the curve for recycle flow due to the acceleration of the blades used in the turbine meter and some coasting after recycle is shut off at the start of deceleration. In spite of this, there is a marked similarity of shape. Quantitative measurements at the peak values and 30 MPH cruise generally agree within a few % recycle.

Cooling of the recycle gas with the present setup is much better out on the road, even in the summer, than on the stand. Cruising at 70 MPH with about 12% recycle in the Plymouth, for example, gave a recycle temperature of close to 300°F; higher temperatures are often reached on the stand with lower speeds and loads.

Fouling of the throttle plate by the dust, etc., in the recycled exhaust has not been a problem. This may be due to the detergent in the Esso Extra fuel used for winter road tests after the dynamometer tests with the Indolene fuel standard for pollution tests. This is one of the areas needing farther study.

Another possible source of trouble would be serious changes in muffler back pressure due to corrosion, etc. We have been assured by those familiar with this problem that before the change of muffler back pressure was serious, the noise level would have forced its replacement. Part way through the test program (9/9/68), a partial plug was found in the exhaust system at Stand 1 which caused an extra pound or two of exhaust back pressure. This caused much more recycle at Stand 1 than corresponded to the same orifice size when tested on the road or on other stands.

To minimize the effect of the unwanted variables, the NO reduction data were usually obtained in back-to-back hot engine tests so that the cycles with and without recycle were only a few minutes apart. Thus, in the 7 cycles of the typical California test as worked up by the computer, the first four cycles (after warm-up) might be made using recycle and the last three without recycle. The computer then averages the recycle results as cycles 1-4 and non-recycle results as cycles 5-7. This way (possible because of the shutoff valve available in the recycle line), we feel the comparison is about as direct and reliable as possible. Such back-to-back runs are shown in the summary tables in the Appendix, as data both with and without recycle on the same horizontal line.

Three types of dynamometer tests were made with the cars.

(a) California Cycles - Chevrolet results are given in Appendix Table A-3.5, Plymouth results in Appendix Tables A-3.1 and A-3.2.

(b) "U.S. Public Health Service" Cycles - Using analyses of total exhaust as collected in bags. Chevrolet results are given in Appendix Table A-3.6, Plymouth in Appendix Table A-3.3.

(c) Steady-State (Cruise Type) Tests - Chevrolet results are in Appendix Table A-3.7, Plymouth in Appendix Table A-3.4.

3.3.2 Exhaust Gas Recycle Greatly Reduces NO_x Emissions

3.3.2.1 Chevrolet NO_x Emission

Actual values of NO_x content in the exhaust varied over a wide range. They were quite dependent on both air humidity and air/fuel ratio; this later was evaluated in terms of % CO which varied more or less directly with air/fuel ratio. Sufficient data were available, especially for the ZERO RECYCLE case to permit computer regressions to separate the variables. This was done, assuming either a logarithmic (exponential) relation for the dependent and/or independent variables or a first power relation. The computer in each case tested the success of the equation in correlating all the data points and calculated a statistical "F" test on the data.

The large number of California cycle data points for the ZERO RECYCLE case with the air-conditioner in use were correlated very well by the relation:

$$\ln (NO_x) = 7.890 - 0.433(CO) - 0.00353(H)$$

where: (NO_x) = ppm NO_x
(CO) = % CO
(H) = humidity, grains H_2O/lb. dry air

Figure 3.16 shows the correlation expressed as ppm NO_x vs. H for four values of % CO. The great dependence of NO_x on both humidity and fuel mixture is evident. Once the computer had segregated the effects of these two variables and established their mathematical coefficients, it was feasible to adjust all the data points to a common humidity level. A value of 40 grains/lb. dry air was chosen as a good average value; it corresponds to 40% relative humidity at 68°F. The equation for adjusting to H = 40 is:

$$\ln (NO_x)_{adj} = \ln (NO_x) + 0.00353 (H-40)$$

The adjusted data at zero recycle and at various recycle rates are shown in Figure 3.17. Computer regressions obtained for the "ZERO RECYCLE, air-conditioner off" data and for the 17.3% inert recycle data are also shown as solid lines. At other recycle rates, data were too few to permit meaningful computer regressions. Lines with a slope parallel to those obtained from the computer regressions were faired through the data.

FIGURE 3.16

NO_x VS. ABSOLUTE HUMIDITY

Chevrolet With Air Injection - Air-Conditioner On
Hot California Cycle With Zero Recycle
Computer Regressed

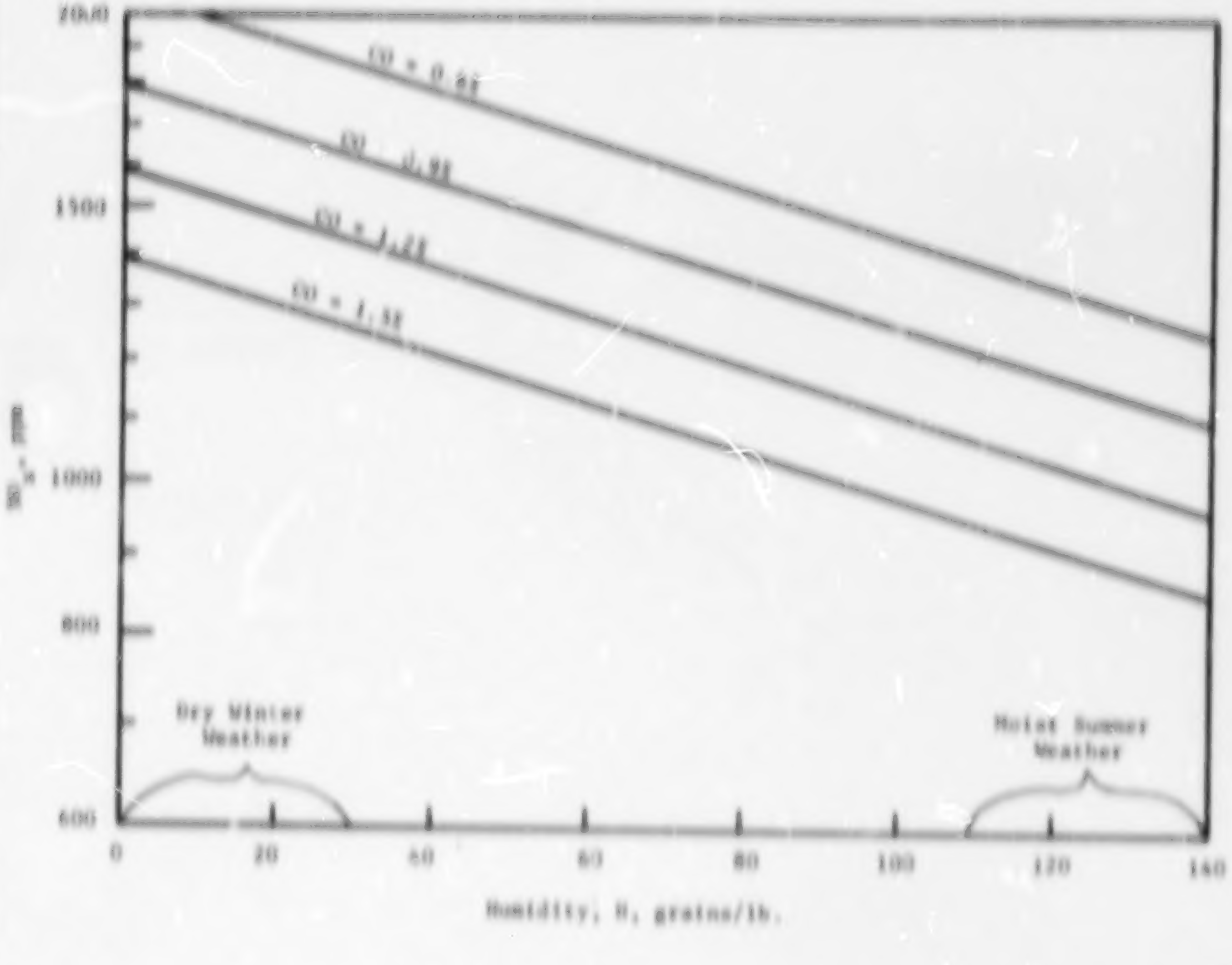


FIGURE 3.17

ADJUSTED NO_x VS. % CO

Hot California Cycle - Chevrolet With Air Injection

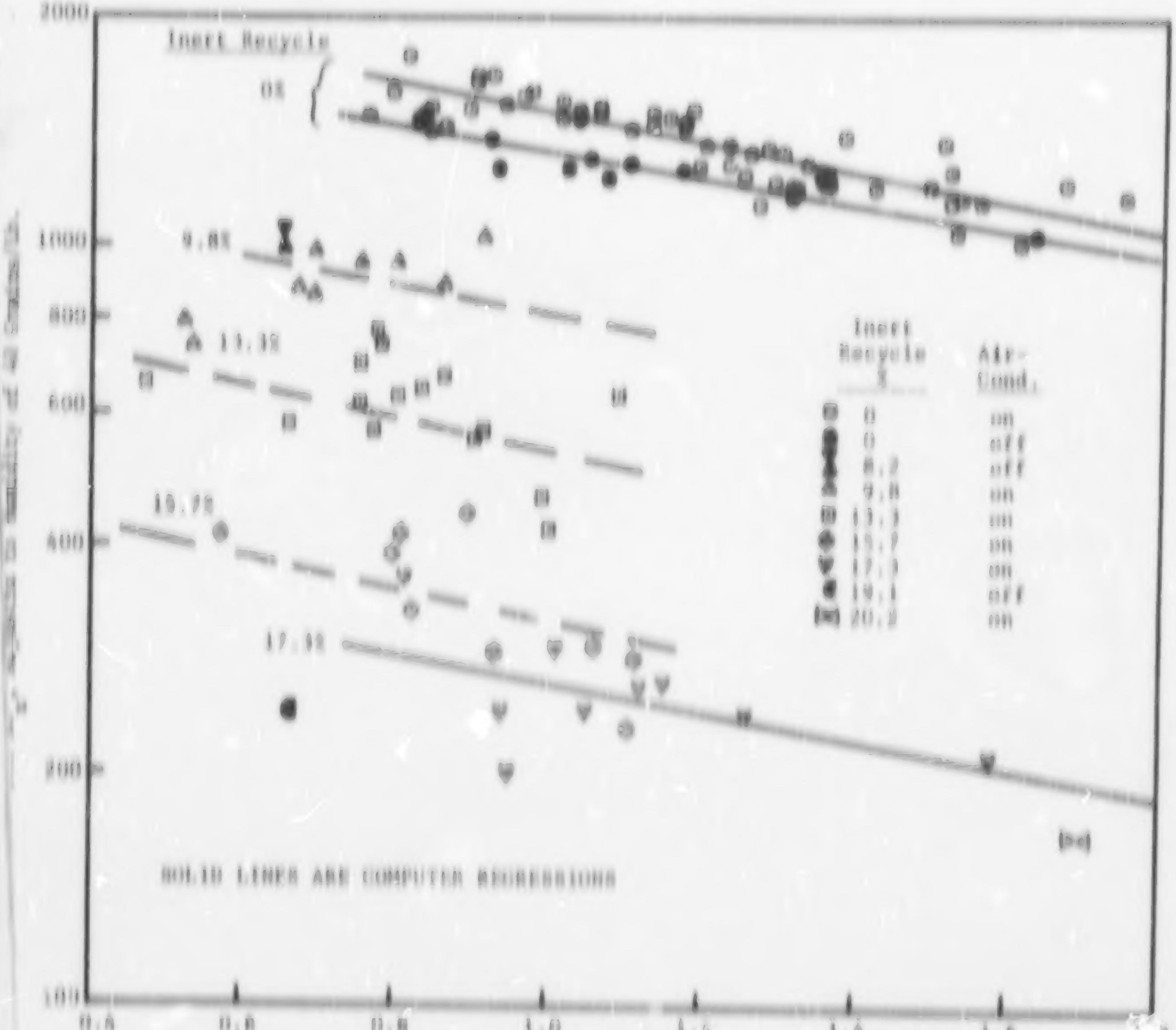


FIGURE 3.18

ADJUSTED NO_x VS. RECYCLE

Chevrolet With Air Injection
Hot California Cycle

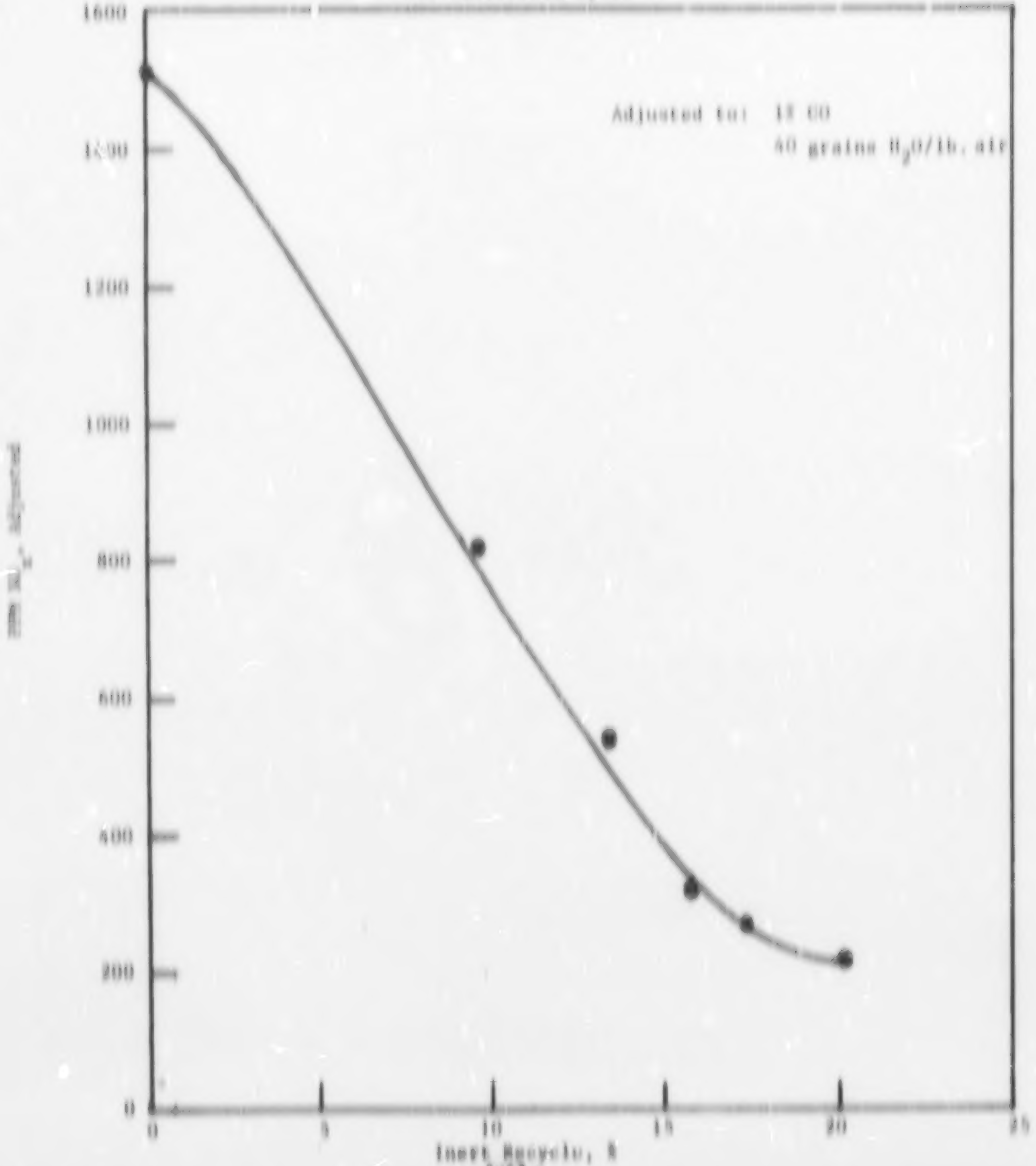
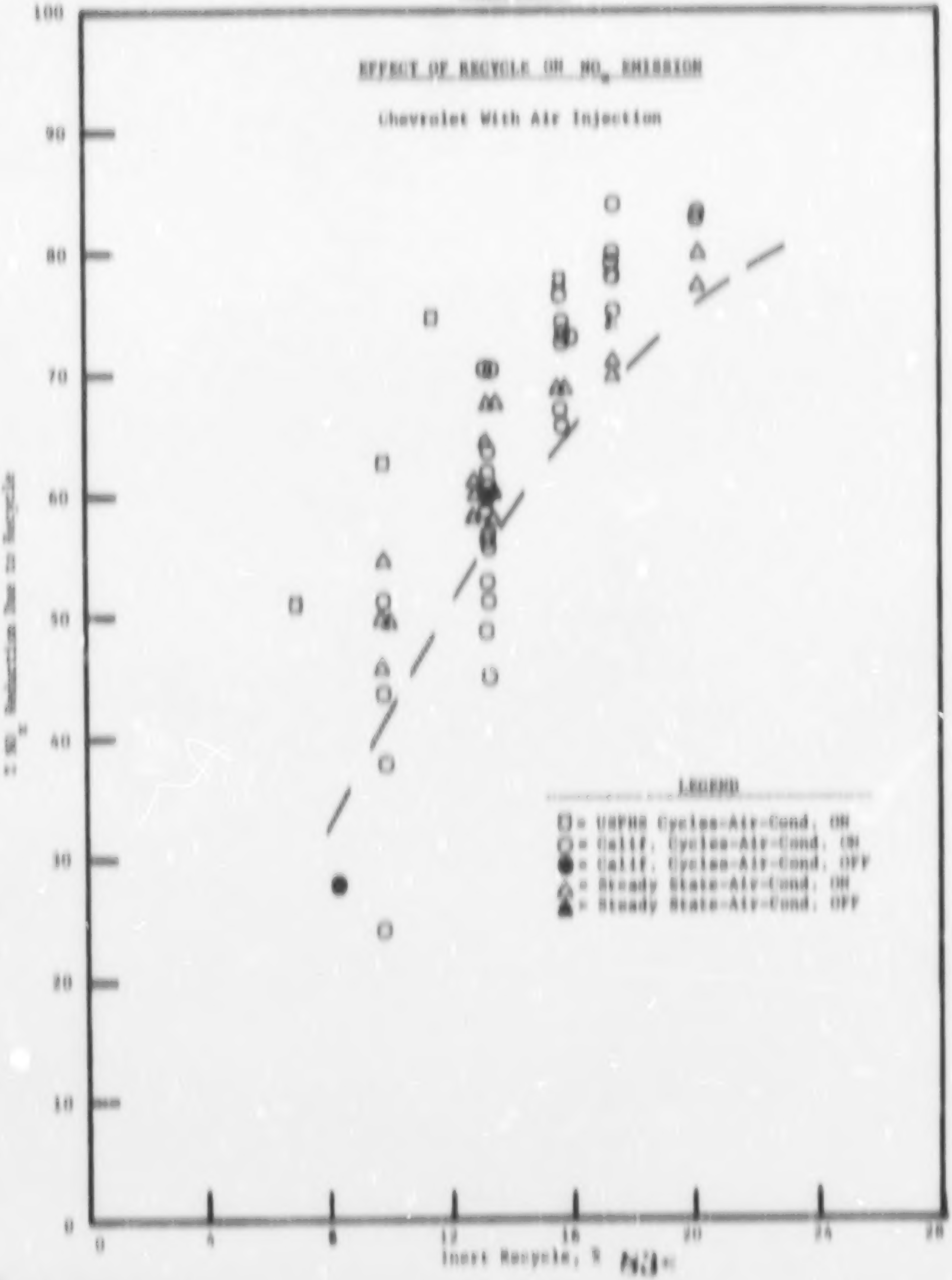


FIGURE 3.19


EFFECT OF RECYCLE ON NO_x EMISSION
Chevrolet With Air Injection
% NO_x Reduction Due to Recycle
Inert Recycle, %
0
4
8
12
16
20
24
28
0
10
20
30
40
50
60
70
80
90
100
LEGEND
□ = USPHS Cycles-Air-Cond. ON
○ = Calif. Cycles-Air-Cond. ON
● = Calif. Cycles-Air-Cond. OFF
△ = Steady State-Air-Cond. ON
▲ = Steady State-Air-Cond. OFF

It is clear that considerable reductions in NO_x can be obtained by the use of exhaust recycle. A cross-plot, at 1% CO of adjusted NO_x vs. percent inert recycle is shown in Figure 3.18. The ZERO RECYCLE value of 1520 ppm NO_x decreased to 540 ppm with 13.3% inert recycle and to 330 ppm with 15.7%, corresponding to NO_x reductions of 64% and 78% respectively. As will be seen later, driveability was good with 13.3% recycle and borderline with 15.7%.

Figure 3.19 shows the percentage reduction in NO_x attained by the use of recycle for steady-state operation and for USPHS and California cycles. Somewhat higher percentage reductions were obtained in the USPHS cycles--these cycles are somewhat more demanding in power and thus give recycle more of a chance to reduce NO_x.

3.3.2.2 Plymouth NO_x Emission

The data from the Plymouth covered a longer time span and wider variations in operating conditions. It did not "hang together" as well as the Chevrolet data, although there was more of it to correlate. The data without recycle were subjected to computer regression separated as to which distributor (spark advance) was used. This analysis showed that humidity did have a marked effect on NO_x but that % CO had only a minor effect. This suggests that the leaner operation employed in the Plymouth is on the flat top of the curve of NO_x vs. air/fuel ratio. The computer equation for best fit of the data with the Mod.-1 distributor is:

$$\ln (NO_x) = 7.743 - 0.0366(CO) - 0.00441(H)$$

where: (NO_x) = ppm NO_x
(CO) = % CO
(H) = humidity, grains/lb. air.

The data, adjusted to a humidity of 40 grains/lb., are shown plotted in Figure 3.20. The recycle data included on that plot are those obtained through September 5, 1968. Following that date, modifications were made reducing the test stand exhaust receiving system pressure drop. This apparently caused less reproducible operation with the Plymouth and the ensuing data from that vehicle scattered badly.

A cross-plot at 1% CO taken from Figure 3.20 is shown on Figure 3.21. The general trend is very similar to that obtained with the Chevrolet: exhaust gas recycle drastically lowers NO_x emission. Plots of percentage NO_x reduction in back-to-back steady state, California cycles and USPHS cycle tests are presented in Figures 3.22 and 3.23.

3.3.3 Spark Timing and Recycle Both Affect NO_x Emissions and Fuel Economy

The laboratory studies with the Plymouth engine had shown a net advantage for a more advanced spark schedule when using exhaust gas recycle. This was the basis for selecting the Mod.-1 distributor for

FIGURE 3.20

ADJUSTED NO_x VS. % CO

Hot California Cycle - Plymouth
Data 6/13/68 - 9/5/68

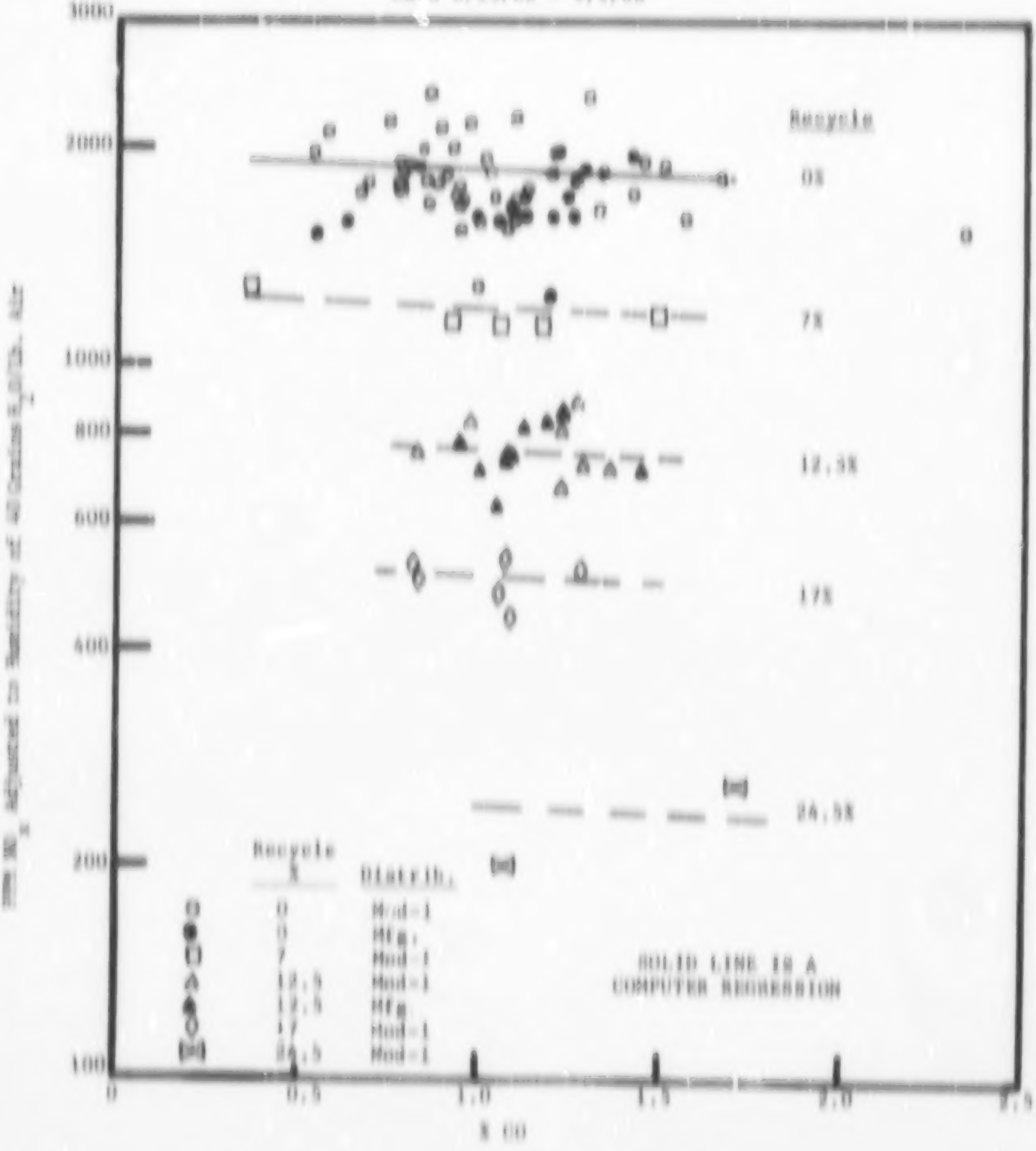
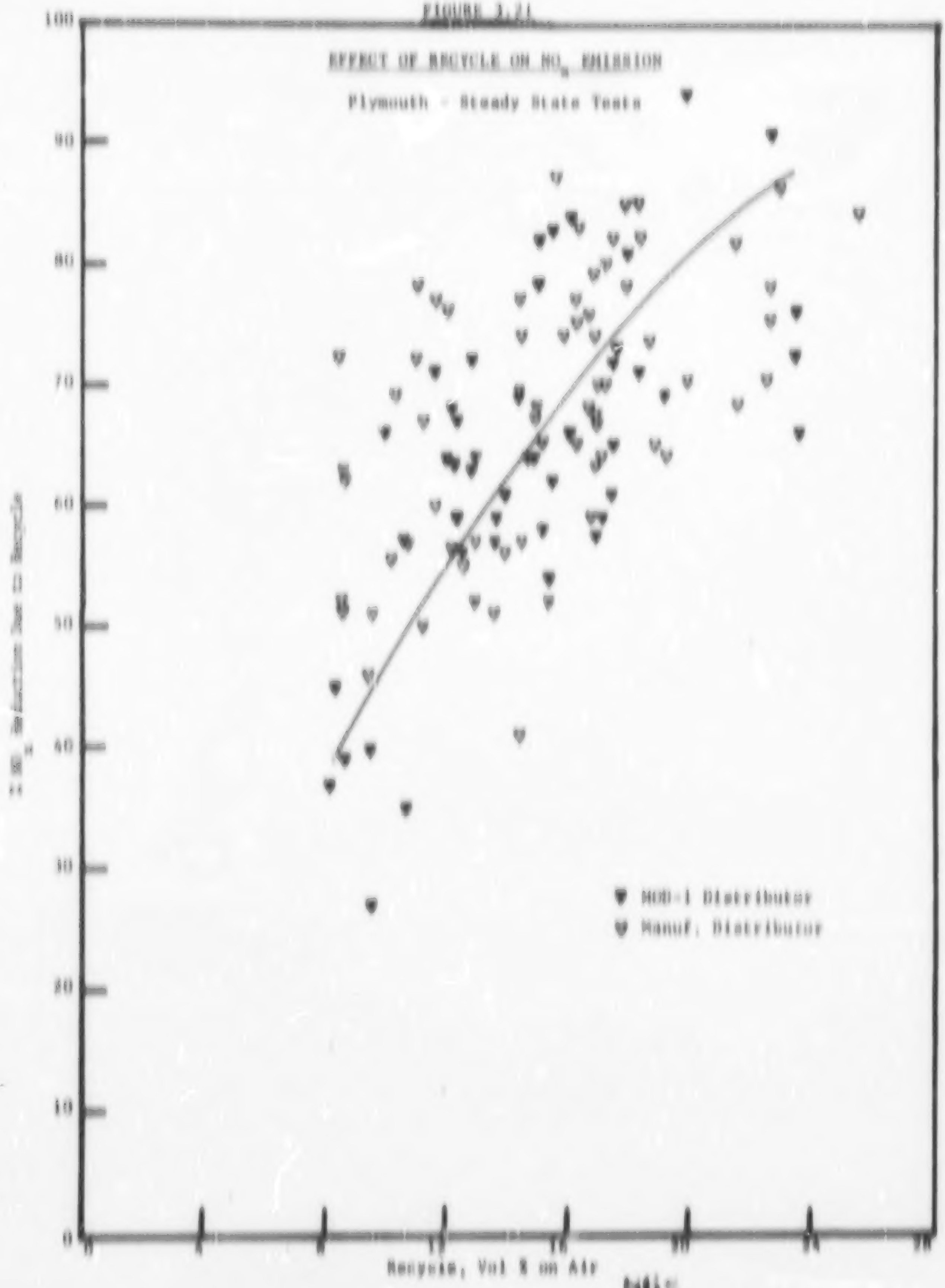


FIGURE 3.21



EFFECT OF RECYCLE ON NO_x EMISSION

Plymouth - Steady State Tests

FIGURE 3.22

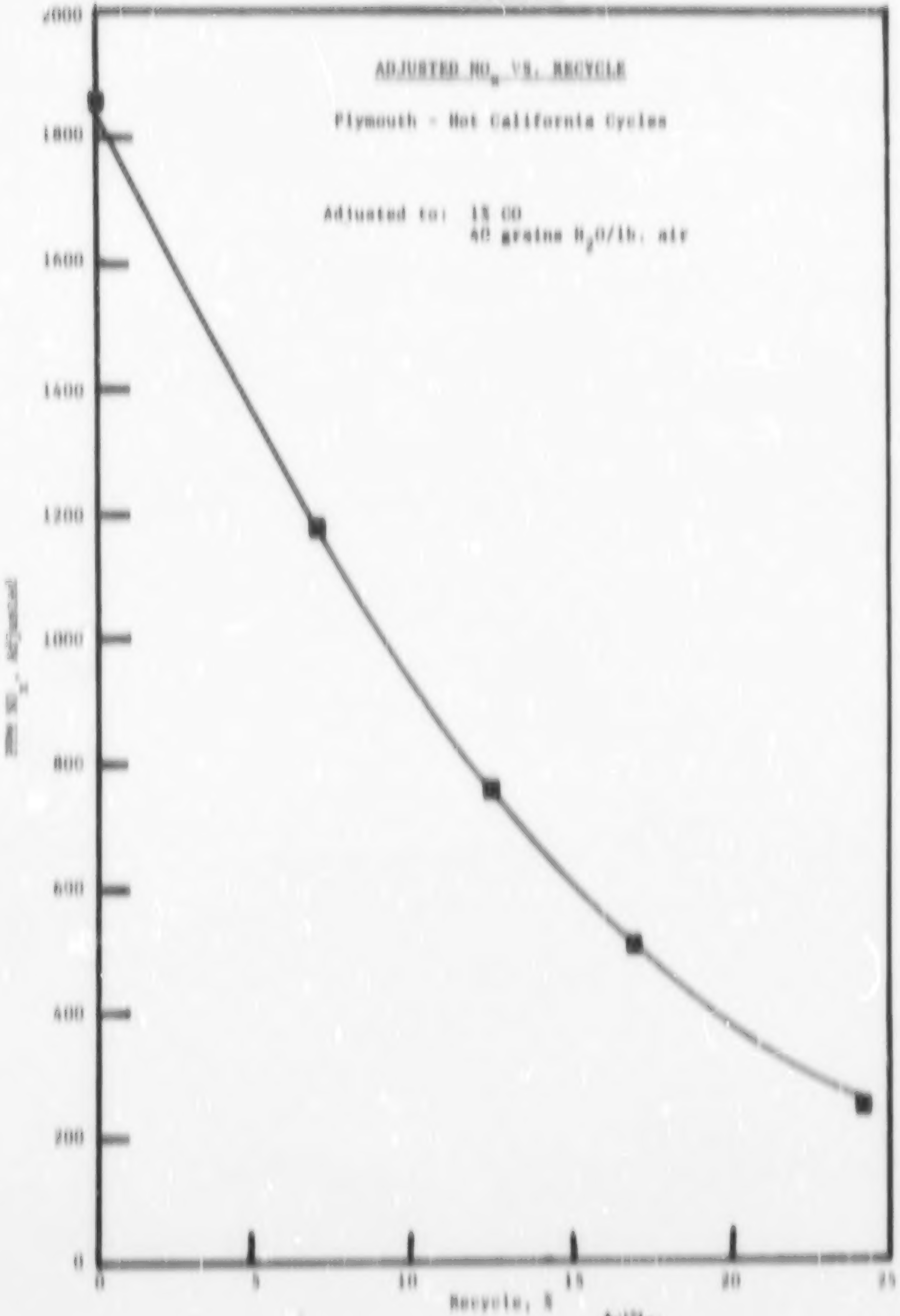
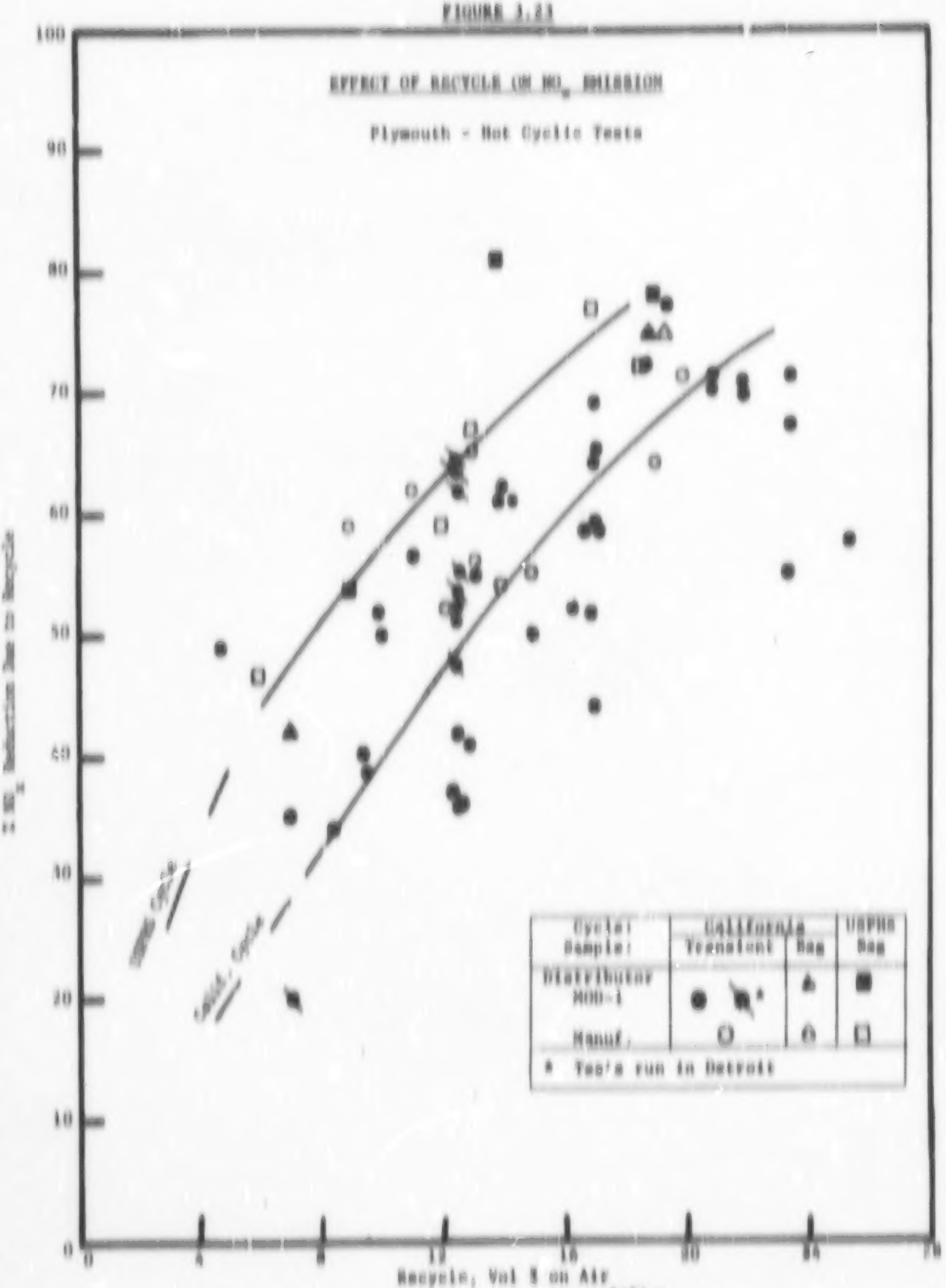

ADJUSTED NO_x VS. RECYCLE
Plymouth - Hot California Cycles
Adjusted to: 1% CO
40 grains H_2O/lb. air
PPM NO_x, Adjusted
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
Recycle, %

FIGURE 3.23



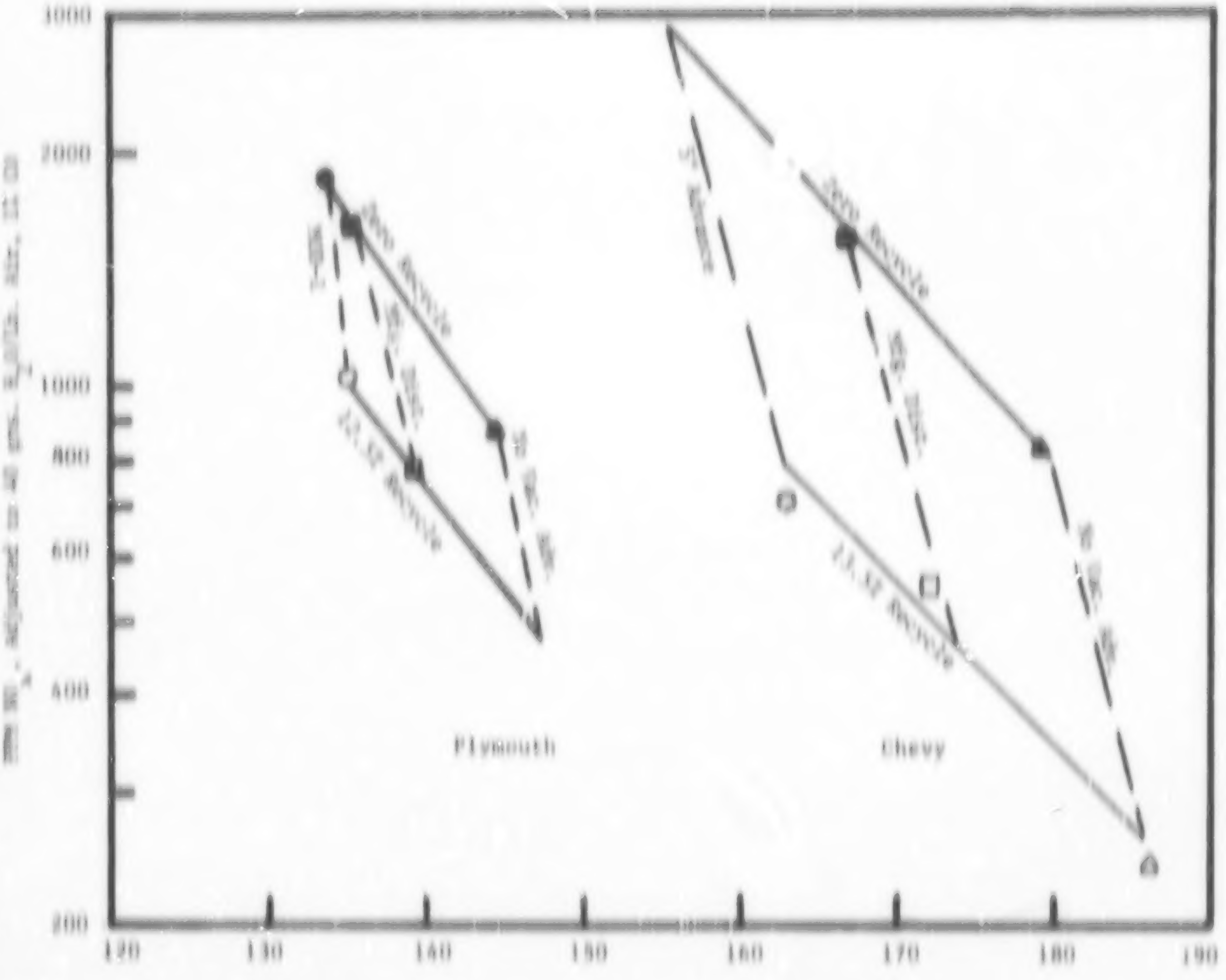
EFFECT OF RECYCLE ON NO_x EMISSION

Plymouth - Hot Cyclic Tests

FIGURE 3.26

EFFECT OF SPARK ADVANCE AND RECYCLE

California Cycle Data



most of the work with the Plymouth vehicle. (The vacuum advance with the Mod.-1 distributor occurred over a wider range of engine manifold vacuum so the timing was more advanced until almost wide-open throttle.) See Figures 3.13 and 3.14.

Results obtained with the Plymouth and Chevrolet cars are listed in Table 3.2 and plotted in Figure 3.24. For each car, data are presented for three different spark schedules--more advanced, manufacturer's and less advanced, i.e., without vacuum advance--and for two recycle rates--zero and either 12.5% or 13.3%.

Table 3.2

Effect of Spark Advance - California Cycle Data

NO_x adjusted to humidity of 40 grams/lb.
dry air and CO = 1.0%

	Plymouth			Chev. (Incl. Air-Cond.)		
Distributor Curve	% Recycle	NO_x (ppm)	Fuel Penalty (%)	% Inert Recycle	NO_x (ppm)	Fuel Penalty (%)
Manufacturer's	0	1610	0.0	0	1510	0.0
Mod.-1	0	1860	-0.9	--	--	--
Vacuum Advance OFF	0	880	6.6	0	835	7.5
Manufacturer's	12.5	780	2.7	13.3	540	3.6
5° Spark Advance	--	--	--	13.3	700	-2.1
Mod.-1	12.5	1020	0	--	--	--
Vacuum Advance OFF	--	--	--	13.3	235	11.5

The patterns observed for both cars were similar: exhaust gas recycle (at constant spark schedule) drastically lowers NO_x at a slight fuel consumption penalty, spark retard (at constant percent recycle) lowers NO_x at a higher fuel penalty. The effect of spark retard alone is about 6.5% reduction in NO_x per % fuel penalty compared to 16.5% reduction in NO_x per % fuel penalty for exhaust gas recycle alone. The two effects seem to be independent. It is, therefore, possible to operate with recycle and some spark advance and thus obtain NO_x reduction without fuel penalty.

The difference in fuel consumption levels between the two cars is presumably due to such factors as the Chevy running richer (with AIR injection) and being tested with the air-conditioner operating, while the Plymouth ran leaner using a CAS system and did not have air-conditioning.

A greater advance in spark timing is possible when recycling because the reactions in the cylinder are slowed by dilution and by cooling with the recycle. Also, some of the "advance" actually is compensating for the retarding effect of the decreased vacuum resulting from use of recycle. With about 13% recycle, the vacuum difference is 1 to 2 inches at light loads to as much as 6 or 8 inches at heavy loads (such as acceleration peaks for the Chevrolet's California cycles). The Mod.-1 distributor on the Plymouth in most ranges of operation advances the spark a few degrees more than the lost vacuum due to recycle will retard it, so there is a net spark advance with it.

With the 5° advance in basic timing, the Chevrolet's "driveability" on the dynamometer using recycle was noticeably better than for the runs without such advance: some of the power loss due to recycling was restored. Here again the 5° advance is more than ample to compensate for the spark retard caused by the lowered manifold vacuum when recycling, except during the heaviest acceleration (15-50) when vacuum goes much lower with recycle and spark may be retarded as much as 12-14 degrees. A general advance is, however, not a good substitute for a properly tailored vacuum advance curve.

3.3.4 "Driveability" Sets a Limit on Recycle

Extensive "driveability" tests of both cars were made both without recycle and with two or three recycle rates that were of most interest. Some tests were made on a level drag-strip about 0.7 miles in length; this was especially good for acceleration time measurements. Other tests incorporated in the "Cold" and the "Warm" Driveability Evaluations of the Automobile Manufacturer's Association were made with the Plymouth on an unopened stretch of Interstate highway about six miles in length, suitable for tests up to 70 mph. Some tests were also made on local roads during the winter to evaluate effects of recycle on cold starting and warm-up performance.

As might be expected, recycle does decrease power for a given throttle opening. Thus, unless recycle is shut off at WOT (wide-open throttle), maximum acceleration will suffer. Actual quantitative results are shown in Table 3.3. Likewise, WOT performance on a long, steep hill would show a difference. But since WOT is seldom used in normal driving, this should be no handicap.

Table 3.3

Effect of Continuous Recycle on WOT Acceleration Times

% Inert Recycle	Test Setup	WOT Acceleration Time, Seconds 0-50 mph	0-60 mph	0-70 mph
Plymouth:				
0	Mod.-1 Distrib.	--	11.76	15.23
0	Same-No Vacuum Adv.	--	11.82	15.30
0	Mod.-1 Distrib.	9.40	12.60	15.7
7	Mod.-1 Distrib.	10.43	13.68	--
9.5	Mod.-1 Distrib.	10.50	14.22	17.2
12.5	Mod.-1 Distrib.	10.82	15.0	19.7
Chevrolet:				
0	Normal, .053" Jets	12.57	16.6	22.73
0	Leaner, .052" Jets	--	16.5	22.1
0	Spark Advanced 5°	--	16.08	21.06
0	Vacuum Advance OFF	--	16.38	21.38
13.1	Spark Advanced 5°	--	17.95	25.07
13.3	Normal, .053" Jets	--	19.43	28.2
15.7	Normal, .053" Jets	--	21.9	30.8
17.3	Normal, .053" Jets	14.6	--	29.0
20.2	Normal, .053" Jets	14.5	26.3	33.2*
20.2	Richer, .056" Jets	14.3	--	27.8
20.2	Leaner, .052" Jets	--	26.6	39.5*

---

* Engine missing - especially after shift above 55 mph.

With recycle rates up to 12.5% in the Plymouth, there was hardly enough loss in "driveability" to be detectable, even by experts, in ordinary driving around town and on throughways up to 70 mph. The AMA type tests showed no appreciable debit at 9.5% recycle. With 12.5% recycle, both the wide-open throttle (WOT) and part-throttle accelerations showed trace to moderate amounts of "hesitation" and trace "surge". All other items on the tests were satisfactory. Experts in Detroit who rated the car for driveability pronounced the 12.5% recycle acceptable and the 17% recycle below borderline but with a good chance of making it satisfactory by further testing and adjustment. The Plymouth driveability data are summarized in Table A-3.8 in the Appendix.

When recycle is added to the idling engine, it slows down 50-80 rpm and operates rougher. This can largely be corrected by readjusting the carburetor. With the equipment as installed some "rumble" was heard when recycle was turned on at idle. At higher speeds, it may be masked by the engine noise. Again, Detroit experts could probably handle such a problem in acoustics without much trouble; the ones we talked with did not seem concerned about the rumble. Moreover, there is little need for recycle at idle, thus any practical system will avoid the problem.

Cold starting and warm-up tests again showed the 12.5% recycle to have little debit. Actually, the tests with a 30°F engine temperature without recycle showed repeated bucking, stalling, hesitation and backfire when the accelerator was floored from a standing start. Using the 12.5% recycle, the results were not appreciably different for either WOT or part throttle accelerations than with zero recycle. With about 17% recycle, the hesitation, etc., at WOT persisted for about 1/2 to 1 mile farther during warm-up than the 1.5 miles for zero recycle operation. Otherwise, performance was no worse with recycle. The part throttle accelerations were satisfactory right from the 30°F start, even with 17% recycle. Apparently, this car cannot be accelerated wide open with a cold engine so all recycle does is prolong the warm-up time slightly. Moreover, during choked, cold start operation, NO_x production is low and there is little need for recycle. Practical systems thus would not use recycle during cold starts.

The driveability results with the Chevrolet were quite similar to those with the Plymouth, expect that on warm-up from a cold start, it was the part throttle rather than the wide-open throttle accelerations that evidenced stumbling and hesitation. Driveability in general seemed satisfactory up to about 13.9% inert recycle. The 15.7% recycle would be borderline on acceptability. All the Chevrolet driveability data are summarized in Table A-3.9 in the Appendix.

3.3.5 Data are Quite Variable for Several Reasons

As one might suspect, these test cars are far from accurate laboratory instruments. Considerable variations in data occur. Several reasons help explain it. First, there are bound to be driving variations from cycle to cycle and test to test. We probably have less such variation at our stands than at most laboratories because the cycle to be followed is plotted on a much larger scale than usual: 50 mph covers almost 8 inches instead of the usual 3 to 5 inches we have seen used elsewhere. Also, our pointer moves instead of the trace lines to be followed and the entire trace is visible at all times; this makes it easier for the operator to follow. Generally, we will match the prescribed speed to better than 0.5 mph.

3.3.5.1 Recycle Gas Temperature

Part of the scatter of the recycle data results from variations in temperature of the recycle gas at the flow restricting orifice. To get a gas volume to compare with the air volume, the volume of the partially cooled recycle gas must be corrected to air temperature.

Every reasonable effort should be made to cool the recycle gas for two reasons. First, the variations in temperature at the orifice will be less so the recycle ratio will be more consistent for a given orifice. Then too, the temperature will govern the amount of heat transmitted by radiation, conduction and convection to the carburetor. Such heat can cause excessive fuel vaporization and enrichment of the mixture. In the lab, it was not practical to cool the recycle piping as fully as it was cooled on the road at usual driving speeds. Several miles of continuous driving at 70 mph over rolling terrain with the Plymouth during the summer never produced recycle temperatures over 300°F. Steady-state operations at equivalent loads on the dynamometer gave higher temperatures than found on the road. Even more cooling than we provided would be advisable.

3.3.5.2 Humidity

Another variable is the absolute humidity of the air. Figure 3.25 is a correlation of hot California cycle NO_x emission for the Plymouth without recycle against absolute humidity of the air; it shows NO_x increasing from about 1250 ppm on a hot, humid summer day to over 2100 ppm on a cold, dry winter day. No adjustment for air/fuel ratio has been made as the Plymouth data were not too sensitive to CO level.

The computer regressions for the Chevrolet and Plymouth gave coefficients corresponding to a 4% change in NO_x for a humidity change of 10 grains/lb.

3.3.5.3 Carburetor Design

Another source of variation, at least when the overall pollution picture is considered, stems from the carburetor design itself. We refer to the stepwise changes of air/fuel ratio as load or throttle position changes; this results from the multiplicity and types of jets (7 in the Plymouth, 6 in the Chevrolet) feeding fuel into the air system. Anything (such as recycle) which causes the throttle position to change for a given load, or the vacuum to change, will cause mixture variations. This can cause serious variations in the CO and hydrocarbon emissions as well as small changes in NO_x. The results for any particular prescribed cycle may be fortuitous--or may even be doctored to "beat" that cycle. To illustrate this point, consider the data in Table 3.5 below. These are steady-state cruise tests with and without recycle made after a series of California cycles with the Plymouth. The car was at its normal operating temperature.

PB-270 015 JUL 69 FLD/GP 13F 21G

EVALUATION OF EXHAUST RECIRCULATION FOR NOX CONTROL. VOLUME I, AND VOLUME II. APPENDIX.

ESSO RESEARCH AND ENGINEERING CO., HOUSTON, TEX. PRODUCTS RESEARCH DIV.

FIGURE 3.25

EFFECT OF HUMIDITY ON NO_x EMISSION

1987 318 CID Plymouth

Hot Cycle - No Recycle

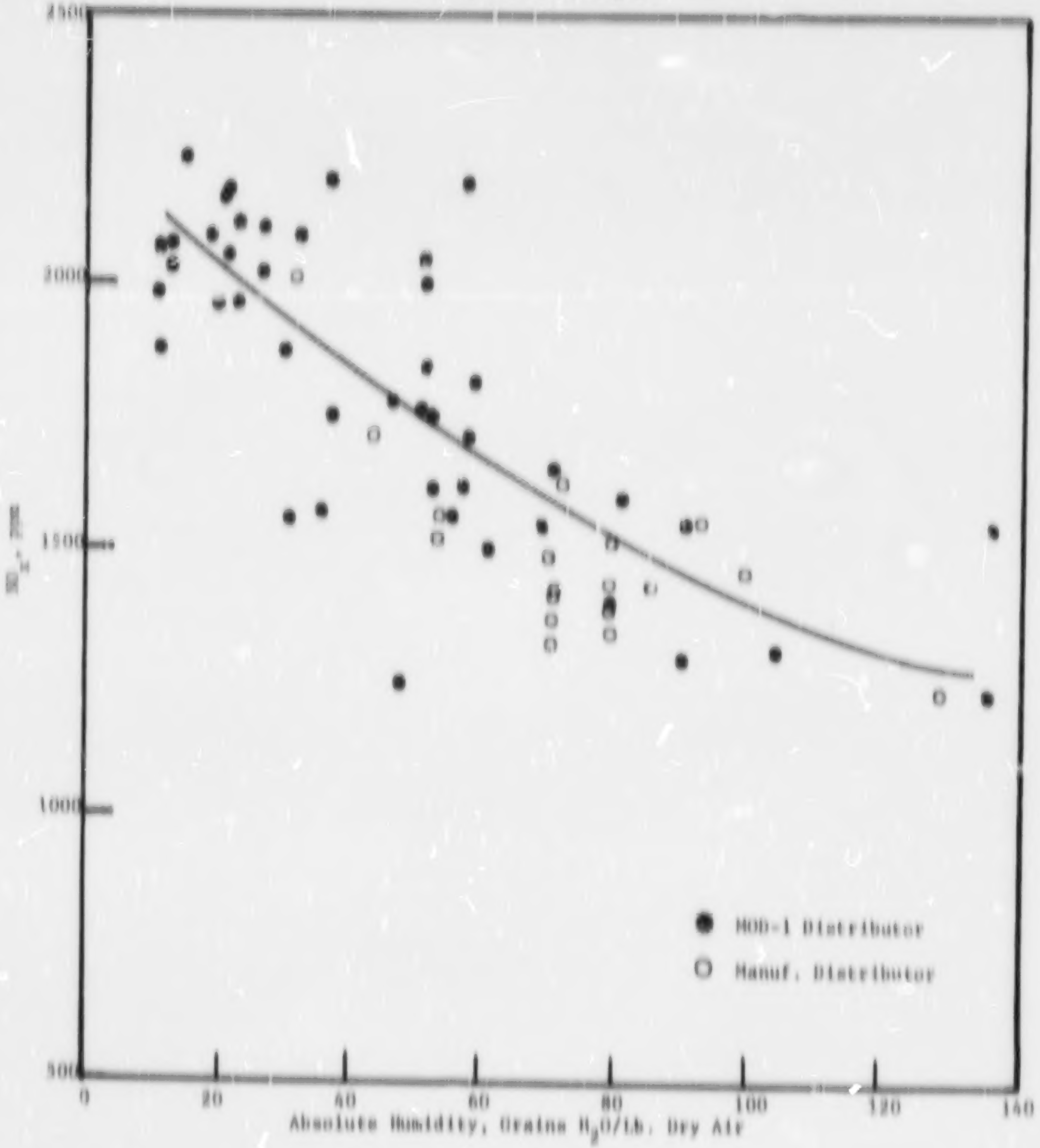


Table 3.4

Steady State Data - Plymouth Car Emissions

Speed (mph)	Without Recycle NO$_x$ (ppm)	CO (%)	HC (ppm)	With Recycle (~17%) NO$_x$ (ppm)	CO (%)	HC (ppm)
20	255	0.53	302	180	0.90	338
30	1550	0.35	301	630	1.56	393
40	2080	0.38	266	675	0.41	277
50	2360	0.90	215	1000	0.38	222

Note that at 30 MPH the new position of the throttle and/or the inch or so lower vacuum resulting with recycle cause a serious increase in CO level. The same is true to a lesser extent at 20 MPH, but at 40 MPH there is no significant change and at 50 MPH the recycle causes a large drop in CO. Thus, conclusions about the effect of recycle would depend on the speed or test cycle involved. For this particular car, on this particular day recycle might look bad for CO if the California cycle is used where the only significant steady-state operation is at 30 MPH but it would look good for CO if the USPHS cycle is used since this has steady state operations near 20, 40 and 50 MPH. We feel sure the whole emission problem would be on firmer ground if the carburetor could be constructed with a single smoothly variable jet instead of the hodge-podge of steps used now. The three small intermediate (so-called "transfer") jets in the wall of the carburetor throat alongside the edge of the throttle plate when it is only slightly open are especially prone to be a source of variation: the slightest change in position of the throttle affects the ratio and amounts of fuel and air coming from them. Most driving will be in the range where these jets are functioning.

3.3.5.4 Small Pressure Drops in Inlet Air System

In order to measure the relative amount of recycle, it was necessary to measure the air flow rate into the carburetor. The added ΔP through the Meriam flowmeter used for this is less than two inches of water maximum during the California cycle. This was not expected to affect operation of the carburetor since the bowl where fuel level is established is vented to the top of the venturi by a relatively large (1/4") diam. tube to effect a pressure balance on the jets. In effect, the pressure drop due to the flow meter is additive with that across the air filter supplied with the car. The latter ΔP has been found to be 1.3 inches of water at the peak of the California cycle 15-50 acceleration with a clean filter; after use, the car air cleaner could conceivably increase by more than that added by the flow meter.

It was found in practice that disconnecting the air flow meter while the engine was idling usually caused a radical change (50% drop) in CO in the exhaust and a small (13%) drop in hydrocarbons. The carburetor has a small vent that opens on top of the carburetor at idle only, but it is so small compared to the pressure balance tube inside the carburetor we would not expect it to exert appreciable influence on the pressure balancing. The biggest effect is at idle but hot California cycles with and without the flow meter connected giving a direct back-to-back comparison at all 7 modes show serious effects in other modes too. Table 1.5 below gives data obtained on the Plymouth. It will be seen that the largest change is in the CO emission (the most sensitive indicator of a rich mixture) during the modes with least load on the engine.

Table 1.5

Effect of Pressure Drop in Inlet Air System of Plymouth

Date 1968	Mode	Flow Meter Connected NO$_x$ (ppm)	CO (%)	HC (ppm)	Flow Meter Disconnected NO$_x$ (ppm)	CO (%)	HC (ppm)
12/5	Idle Test	--	2.48	204	--	1.27	178
12/9 - Hot Calif. Cycles With 12.5% Recycle							
	Idle	116	2.04	270	142	1.05	284
	0-30 mph	1684	0.73	338	1558	0.84	370
	30	906	0.64	310	698	1.36	332
	30-15	200	1.95	288	192	1.57	402
	15	156	2.01	220	166	1.39	212
	15-50	2166	0.56	322	1878	0.91	344
	50-0	234	1.97	1236	372	1.43	1830
	Wtd. & Avgd.	1531	0.84	347	1349	1.00	384
12/5 - Hot Calif. Cycles Without Recycle							
	Idle	80	2.98	278	86	1.29	284
	0-30	2109	1.17	334	2144	0.83	342
	30	1570	0.62	298	1384	0.55	294
	30-15	286	2.76	238	246	1.45	468
	15	108	2.65	222	112	1.70	214
	15-50	2800	0.80	314	2734	0.92	318
	50-0	454	2.91	1200	430	1.78	1778
	Wtd. & Avgd.	2309	1.21	328	1964	0.93	361

While we have no adequate explanation for the data shown, it does point up another problem to be faced, namely, that minor plugging of a car's air filter can make major changes in the air pollutants emitted, especially in a test such as the California cycle that emphasizes low power modes of driving.

1.3.6 Use of 4,000 Lb. vs. 4,500 Lb. Weights on Dynamometer Has Only Minor Effect on Results

Both cars are on the border between these two weight classes in the matter of specifying which equivalent weight to use for acceleration tests. Recent wording of the regulation would require 4,500 lbs. Since our No. 1 stand can employ only 4,000 lb. equivalent weight we need to know how much this affects results. Data obtained in Detroit and on our No. 2 stand are summarized in Table 1.6.

Table 3.6

Effect of Acceleration Weights - California Cycle Data

Weight (lbs.)	Without Recycle NO (ppm)	Without Recycle CO (%)	Without Recycle HC (ppm)	With Recycle (~12.5%) NO (ppm)	With Recycle (~12.5%) CO (%)	With Recycle (~12.5%) HC (ppm)
Detroit Data						
4000	1648	0.80	342	861	1.37	369
4500	1925	0.87	333	898	1.40	363
Stand 2 Data						
4000	2001	0.87	354	974	0.99	369
4500	2043	0.97	361	994	0.99	382

The Detroit data show a 4 to 16% difference in NO for the lower weight, only minor differences otherwise. The Stand 2 data agree for the two weights within 2% which is within the accuracy of the test. Hence, the results with Stand 1 should be within a few percent of those that would be obtained with the heavier weight.

3.3.7 Recycle Can Improve Fuel Distribution in Multicylinder Engines

A continual problem with multicylinder engines is the variation of air/fuel ratio from one cylinder to another. A clue as to how little or how great this variation is comes from the relative amounts of O_2 and CO in the exhaust. For a single cylinder, both gases would not occur in appreciable quantities at the same time: as the mixture is leaned out the CO decreases almost to zero before much O_2 shows up. In a multicylinder engine, however, imperfect distribution causes some cylinders to run richer than others. The extent of the O_2-CO overlap is a rough measure of distribution efficiency.

We usually find that when recycle is introduced, better distribution occurs as shown by O_2 and CO both decreasing with A/F ratio constant; in other words, the rich cylinders get leaner and the lean cylinders get richer. The effect is not as evident at very heavy loads as it is at the lighter loads characteristic of most driving. This is shown by the steady-state data from 8/13/68 abstracted in Table 3.7 below. The improved distribution may be due to the extra turbulence from the side stream of recycle gas or to better vaporization caused by the higher temperature of this gas, or both.

Table 3.7

Effect of Recycle on Fuel Distribution - Plymouth

% Recycle in Air	Speed RPM	Load (CFM Air)	Exhaust % O_2	Exhaust % CO	A/F (Overall)
0	1500	41	1.43	1.44	14.76
13.2	1500	40	0.82	0.82	14.59
15.3	1500	47	1.00	0.38	14.93
0	1500	44.5	1.20	1.05	14.76
14.8	1500	45	0.87	0.59	14.75
0	1500	[illegible].5	1.20	0.63	14.98
13.9	1500	55.5	0.98	0.31	14.96
0	2000	52.7	1.17	0.84	14.86
14.0	2000	52.3	0.86	0.54	14.82
0	2000	62	1.28	0.61	15.15
15.4	2000	62.5	1.16	0.31	15.19
0	2000	71.5	1.52	0.43	15.43
10.9	2000	71.5	1.47	0.20	15.46

3.3.8 Using Recycle "Continuously" Causes Higher CO and Hydrocarbon Emission

When recycling of exhaust gas was first planned, it was thought desirable not to use recycle while idling or at full throttle. The latter was a concession to the "cowboys" to give them maximum power when desired. In other words, it would preserve the maximum power of the engine. At idle, it was feared that the engine would run too rough, stall and cause trouble in starting. To provide recycle only in the intermediate zone between throttle extremes would complicate "Detroit's" job and run up the cost since it would require some form of shutoff valve in the recycle line.

To see how necessary it really was, several runs were made to compare the two methods of recycling. A few such are summarized in Table 3.8 below. The "automatic" operation cuts out the recycle at the two extremes of throttle movement.

Table 3.8

"Continuous" vs. "Automatic" Recycle

Date	% Recycle	Used Continuously			Used Automatically		
		NO_x	CO	HC	NO_x	CO	HC
California Cycle (computer sampling):							
8/16	22-25	215	1.72	447	163	1.08	263
8/19	5	977	0.93	271	1091	0.38	233
8/27	20-22	483	1.29	366	487	0.82	298
USPHS Cycle (bag sampling):							
8/29	16-19	310	1.35	347	300	0.82	256

As the table shows, no appreciable improvement in NO_x emission is obtained with the extra recycling but it does cause serious increase in CO and hydrocarbon emissions. A check of the computer print-outs shows that most of the harm is done during the decelerations and low-speed cruise modes. This suggests that the recycle should be removed at the idle or low-speed throttle positions. Once this provision is made, it is optional whether it should also be stopped at the full throttle (high load) conditions. If maximum power is the dominant factor, then it should be removed but if minimum air pollution is the criteria, then recycle should be left in because the highest formation of NO_x occurs at high power outputs. In practice, full throttle is seldom used in city driving so it may not matter too much which route is chosen. Recycling during idle did not seriously interfere with starting the engine. It did idle rougher and slower but adjustments could be made to correct this. Detroit will probably make a choice of how to use recycle based on relative costs and simplicity of the necessary equipment. The extent to which maximum power is decreased by recycle was discussed in Section 3.3.4.

3.3.9 Bag Analyses Show Lower NO_x and Hydrocarbon Emissions

Since only a portion of the data in the California cycle is used by the computer, it would be only fortuitous if the analyses of the total exhaust collected in a bag agreed with computer analyses before weighting factors are applied and they don't. Bag samples always show lower NO_x values, due in part to reaction and loss of NO_x. Likewise, the bag samples from the USPHS cycle show 15-40% lower NO_x values than were calculated from the traces: this is more than any residual gas left in the bags might explain. It is known that the NO_x continues to oxidize in the bag and over a period of hours will decrease considerably; whether the 15-30 minute delay in analysis entirely explains the differences may be questioned. The loss of hydrocarbons may well be due to absorption by the wall of the plastic bags. The CO values are not consistently lower and may be, therefore, unaffected. Dilution with any air left in the bag will, of course, lower all values, but this should be quite small. Table 3.9 below summarizes several tests that show this effect.

Table 3.9

Bag Analyses vs. Analyses From Tapes

Date	Type Cycle	Analyses NO - ppm Bag	NO - ppm Tape	CO - % Bag	CO - % Tape	HC - ppm Bag	HC - ppm Tape
6/14	USPHS	300	494				
		405	709				
6/27	Calif.	355	582	1.00	0.91	538	553
		470	661	1.19	1.09	528	590
6/27	Calif.	370	555	1.19	1.15	692	695
		500	670	1.15	1.17	537	645
6/28	Calif.	410	600	1.06	1.00	212	262
		1140	1375	1.07	1.13	233	291
9/10	Calif. on	1040	1309	0.55	0.67		
	(Stand 2)	640	786	0.67	0.95		

3.3.10 Recycle Can Be Used Without Serious Change in CO or Hydrocarbon Emission

3.3.10.1 Chevrolet Tests

The Chevrolet was consistently low in hydrocarbon emission, over a wide range of air/fuel ratios. This results from the air injected into the hot exhaust manifold. However, CO was less easily eliminated by this "secondary" air and varied with air/fuel ratio. We used the CO value to determine the size of fuel jet to use in the carburetor. The air injection complicates any test program because the recycle contains about 5% oxygen (or about 24% air) which serves as part of the charge to the cylinder but does not flow through the venturi to get its share of fuel. Hence, to get a given air/fuel ratio in the cylinder (or a given CO content in the exhaust), it is necessary to use a slightly larger fuel jet when recycling. For the recycle rates of interest (10-17% inerts) the 0.053" jet supplied with the car was proper for CO values slightly below 1.0%. Then, without recycle, a jet diameter of 0.052" was proper for the same CO emission. During the period when these two jets were compared, the hydrocarbon emission values averaged 250 ppm for the 0.052" jet with no recycle and 236 ppm for the 0.053" jet with recycle; this later jet without recycle averaged 231 ppm. These hydrocarbon values agree within the range of experimental variation so represent no significant trend.

3.3.10.2 Plymouth Tests

Perusal of the summary data (Appendix Tables A-3.1 to A-3.4) shows a wide range of CO and hydrocarbon emission values from the Plymouth, both without and with recycle. As explained earlier, much of this variability is the result of the carburetor construction and the changed throttle positions when recycling. If or when recycling is adopted, some redesign of the carburetor will be in order to compensate for the actual throttle positions. This should keep the emissions better under control.

Steady-state data where the water brake was used to give more loading of the engine generally show low values of CO and hydrocarbons. It is the relatively light loads and decelerations of the cycles that gave the higher values. Even so, of 43 recycle tests in cyclic runs with the Plymouth where at least 50% reduction of NO_x resulted, there were 27 in which recycle caused less than 15% change in CO. In only 10 of these was CO increased, in 2 CO remained unchanged and in 15 CO actually was decreased by recycling. These data are shown in Figure 3.26. In virtually all these cases "automatic" recycling was used so that recycle was cut off during the very low power and deceleration modes; if recycling was maintained the CO and hydrocarbons were quite high during those modes due to poor combustion--at least with the carburetor built and adjusted for non-recycle operation. The fact that so many tests were successful in decreasing NO_x by half or more without appreciable increase in CO shows that it is possible.

As for hydrocarbon emissions, this car which was built to give low emissions has always shown more than expected. The early operations gave values of 200-300 but more recent ones give 250-500 ppm. Recycle seldom has much effect on this item--usually an increase of only a few % if any. When the car was returned to the manufacturer for testing and adjustment, the carburetor was rebuilt 11 times until the mixture fitted the desired curve almost exactly. Still, California cycles showed hydrocarbons well above 300 ppm even without recycle. With recycle, it increased 3 to 12 percent. In many tests, however, there was little or no increase in hydrocarbons when recycling.

We may conclude for both cars, therefore, that it is possible to use recycle without appreciable increase in CO or hydrocarbons.

3.3.11 Vehicle Results Check Engine Lab Predictions

As already mentioned, one prediction of the engine lab testing was verified in the vehicle tests--namely, that use of the more advanced spark timing of the Mod.-1 distributor in the Plymouth engine would permit the reduction of NO_x by exhaust gas recycle without loss of fuel economy. In addition, several of the steady-state tests were made at conditions duplicating those used in the lab tests. As shown in Table 3.10, the vehicle results in almost all cases were in agreement with the lab predictions as far as NO_x reduction was concerned.

FIGURE A.26

EFFECT OF RECYCLE ON HOT-CYCLE CO EMISSIONS

All Plymouth Runs With Over 50% NO_x Reduction

(From Table A-3.2)

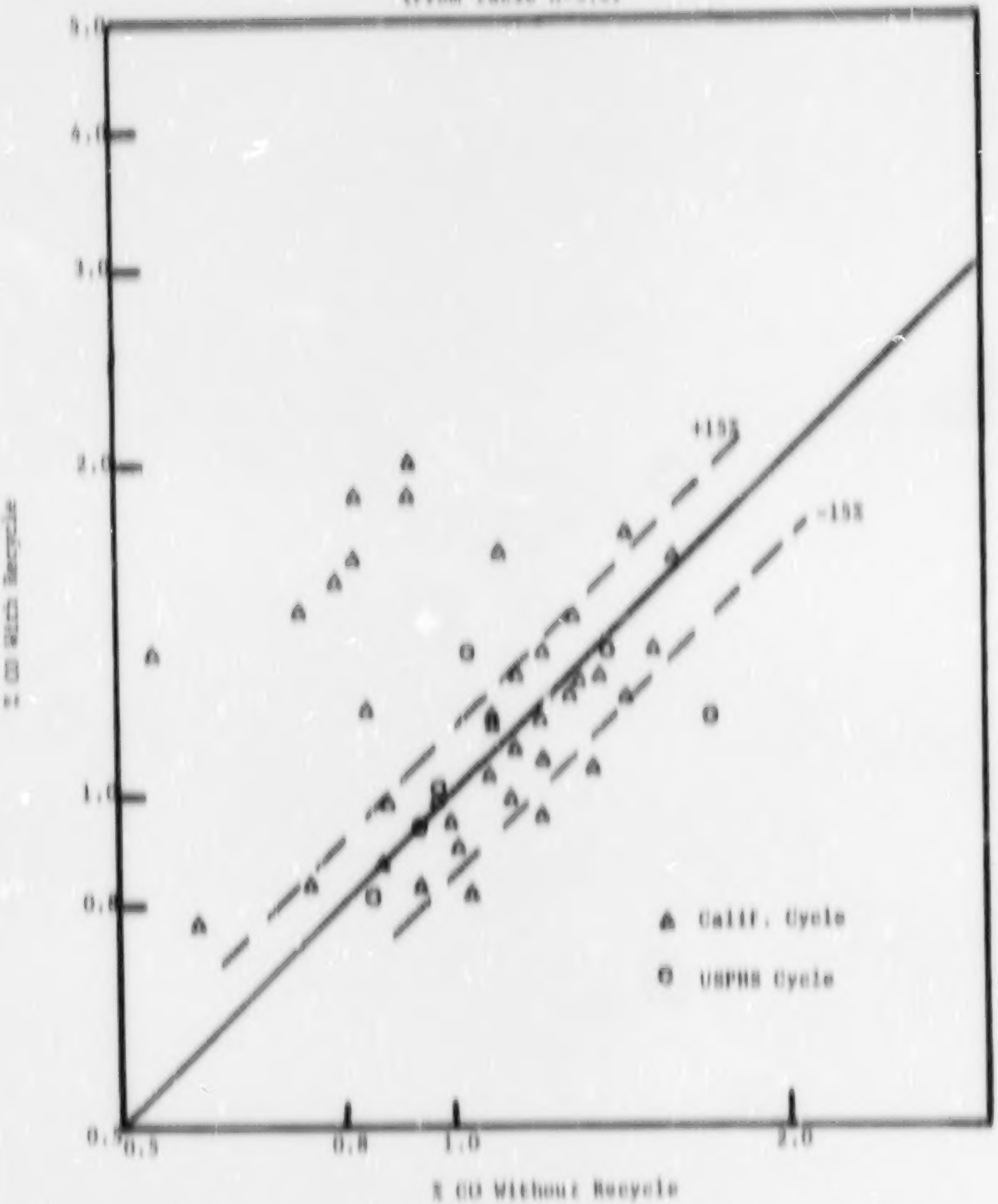


Table 3.10

Lab Predictions vs. Vehicle Results (Plymouth)

RPM	Speed/Load Case	$\frac{NO_x \text{ (Recycling)}}{NO_x \text{ (No Recycle)}}$ Predicted	Actual	Δ	σ for Prediction
1500	1	0.424	0.450	-0.026	0.049
	2	0.385	0.368	+0.017	0.025
	3	0.422	0.452	-0.030	0.045
	4	0.171	0.230	-0.059	0.060
2000	5	0.458	0.468	-0.010	0.043
	6	0.418	0.413	+0.005	0.046
	7	0.388	0.431	-0.043	0.034
	8	0.344	0.309	+0.035	0.048

The average deviation between actual and predicted is -0.014; (prediction is for slightly more NO_x reduction than observed). In only one case was the difference greater than the calculated sigma (standard deviation) of the prediction. Agreement is good, especially considering the many subtle differences in the tests themselves.

No suitable data were obtained for predicting the Chevrolet results.

3.4 CONCLUSIONS

The major conclusions that can be drawn from the vehicle tests are:

1. Exhaust gas recycle is a feasible way to lower NO_x emissions from cars using either air injection or engine modifications to control CO and hydrocarbons.
2. NO_x emission can be reduced about 60% with little or no change in hydrocarbons and CO by recycling inert exhaust gas at about 12.5% of the air rate fed to the engine. Driveability, cold starting, etc., will not be seriously affected with this amount of recycle. Unless recycle is shut off at wide-open throttle, maximum acceleration rates will be decreased.
3. Recycling about 15% of inert exhaust gas will reduce NO_x emission about 67% in the Plymouth and 75% in the Chevrolet. This much recycle, however, gives borderline "driveability".
4. The NO_x emission from the air-injected Chevrolet was quite sensitive to the air/fuel ratio (or CO emitted); the NO_x from the engine-modified Plymouth, which was generally operating with leaner mixtures, was only slightly dependent on the mixture ratio (or CO emitted).
5. Hydrocarbon emissions, which usually have been higher than expected for the Plymouth are affected only slightly if at all by recycling.
6. CO emissions from the Plymouth were very erratic. Usually they were within ±15% of the no-recycle value. Occasionally they were considerably higher. This problem could be minimized by redesign of the carburetor, especially as regards the transfer jets used at low and moderate power.
7. CO emissions from the Chevrolet were more reproducible. They depended on the size main jet used and the idling mixture adjustment.
8. Steady-state tests on the Plymouth vehicle gave results in generally good agreement with predictions from the lab work. No comparisons were possible on the Chevrolet.
9. Humidity can cause variations up to 40% in NO_x production between dry winter and moist summer days. Without recycle, the Plymouth, in a hot California cycle, will emit about 2200 ppm NO_x on a dry winter day and about 1200 on a very moist hot summer day. The figures for the Chevrolet are about 1800 and 1100 respectively.
10. Disconnecting the vacuum advance on the distributor (as proposed to reduce NO_x in older cars) will reduce NO_x about 45% but fuel consumption increases about 7% or roughly 6.5% NO_x reduction/% fuel increase. Recycling will decrease NO_x about 16.5%/% fuel increase or 2.5 times as effectively. Moreover recycling with slightly advanced spark will give NO_x reductions without any fuel penalty.

11. Bag analyses from collections of total exhaust generally give lower values for NO_x and hydrocarbons than direct sampling and analysis; CO is usually unaffected.

12. The simple recycle system using a fixed orifice to set flow rate of recycle gas does a good job of proportioning recycle to the total air throughput.

13. The recycled exhaust gas should be cooled as much as feasible before bringing it into the carburetor throat.

14. Admission of recycle gas to the carburetor between the venturi and the throttle plate improves distribution of the fuel-air mixture among the cylinders.

15. Recycle should be shut off during idle, closed throttle decelerations and periods of very low power. At maximum power (WOT) it can either be left in to prevent the high NO_x emissions at such periods or cut out to preserve maximum engine power and minimum acceleration times.

16. Introducing recycle containing appreciable air between the venturi and throttle plate requires that a larger main jet be employed to maintain the same air/fuel ratio in the cylinder and thus the same CO emission. For the air injection employed in this Chevrolet, a 0.001" larger jet was suitable.

17. Introducing recycle as above decreases manifold vacuum 1-8 inches and may thereby cause spark to be retarded; this in turn further reduces NO_x emission but decreases power and affects driveability adversely.

18 More advanced ignition timing curves (as with the "Mod.-1" distributor) are beneficial when exhaust gas recycle is used; fuel economy is maintained when recycling and driveability is better maintained; the NO_x is increased somewhat but there is still a good net gain for recycle.

19. Slight changes (~1 inch water) in the pressure drop of the inlet air system may cause marked changes in the CO emission during idle or deceleration modes. The condition of a car's air filter is thus important.

FINAL REPORT

Motor Vehicle Emission Lab
LIBRARY

EVALUATION OF EXHAUST RECIRCULATION FOR NO$_x$ CONTROL

Volume II

Appendix

Contract No.: PH 86-67-25
National Air Pollution Control Administration
Department of Health, Education and Welfare

Esso Research & Engineering Co.
Products Research Division
July 1, 1969

108-

LIST OF FIGURES AND TABLES

No.		Page
A2.1	Coefficients for Regression Equations-Plymouth	A-4 to A-5
A2.2	Coefficients for Regression Equations-Ford	A-6
A2.3	Coefficients for Regression Equations-Chevrolet	A-7
A2.4	Coefficients for Regression Equations-Valiant	A-8
A2.5-A2.59	Data for Plymouth	A-12 to A-66
A2.60-A2.86	Data for Valiant	A-68 to A-94
A2.87-A2.115	Data for Ford	A-96 to A-125
A2.116-A2.142	Data for Chevrolet	A-126 to A-152
A2.143	Evaluation of Interactions	A-155
A2.144	Reduced Equations for Effect of A/F Ratio	A-156
A2.145	Reduced Equations for Effect of Spark Timing	A-157
A2.146	Reduced Equations for Effect of Exhaust Recycle	A-158
A2.147-A2.152	Predicted Overall Effects of Recycle	A-159 to A-164
A3.1	California Cycle Tests-Plymouth	A-166 to A-173
A3.2	California Cycle Tests (Detroit)-Plymouth	A-174
A3.3	USPHS Cycle Tests-Plymouth	A-175
A3.4	Steady-State Runs-Plymouth	A-176 to A-180
A3.5	California Cycle Tests-Chevrolet	A-181 to A-185
A3.6	USPHS Cycle Tests-Chevrolet	A-186
A3.7	Steady-State Runs-Chevrolet	A-187 to A-191
A3.8	Driveability Tests-Plymouth	A-192 to A-193
A3.9	Driveability Tests-Chevrolet	A-194 to A-195
A3.10	Adjustment of Recycle Measurements	A-196

BIBLIOGRAPHIC DATA SHEET	1. Report No.	2.	3. Recipient's Accession No.

4. Title and Subtitle
Evaluation of Exhaust Recirculation For NOx Control,
Appendix, Vol. 2

5. Report Date
July 1968

6.

7. Author(s)
Esso Research and Engineering Company

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Esso Research and Engineering Company
Products Research Division
Houston, Texas

10. Project/Task/Work Unit No.

11. Contract/Grant No.
PH 86-67-25

12. Sponsoring Organization Name and Address
National Air Pollution Control Administration
Department of Health, Education and Welfare
Ann Arbor, Michigan 48105

13. Type of Report & Period Covered
Final Report

14.

15. Supplementary Notes

16. Abstracts

The NAPCA-Esso study summarized in this report investigated: Feasibility of the recirculation technique when used in conjunction with positive crankcase ventilation and with the Engine Modification System with Manifold Air Injection; design characteristics needed for an automatic system to provide emission controls while retaining fuel economy and vehicle performance. The goal was to determine the desirability of carrying out further studies concerning long-term operability, effectiveness and engine wear effects of exhaust recycle in combination with hydrocarbon and CO control systems. The program was divided into two phases: a laboratory engine phase where four different engines were operated over a wide range of steady-state conditions and a vehicle test phase where two fully-equipped cars were studied under transient conditions.

17. Key Words and Document Analysis. 17a. Descriptors

Air pollution
Motor vehicles
Exhaust emissions
Nitric oxide
Exhaust systems

17b. Identifiers/Open-Ended Terms

Recirculation technique
Emission control technology
Positive crankcase ventilation

17c. COSATI Field Group

18. Availability Statement Release Unlimited 107<	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages
	20. Security Class (This Page) UNCLASSIFIED	22. Price

A2.0 LABORATORY ENGINE PHASE

A2.1 Data Correlation by Regression Analysis

The regression model and the variables employed are defined in Section 2.1.4

The regression program finds the constant B_0 and the coefficients B_1-B_9 for the best fit equation for each Y_n, with the requirement that any B_i must have an F-ratio value of at least 4.0 if that B_i and the associated X_i are to be included in the equation. It is thus possible, though unlikely, that the equation may contain only square and cross-product variable terms (X_4-X_9). The program assigns the data variance initially to whatever variable has the major effect and then, in steps, assigns the remaining variance to successively less important variables. However, if required to include, for example, the linear terms, X_1-X_3, the variance will be assigned first to these terms and then distributed among the remaining variables. The linear terms are then said to be "forced" into the regression equation. Depending upon the data, the result of forcing the linear variables may be substantial in terms of the accuracy of the regression equation, but is usually small. If the terms would be present (B_i has F-ratio over 4.0) without forcing, there will be no effect unless the sequence of steps followed was changed by the forcing requirement. In other cases, the equation developed with forcing may be either more or less accurate than that without forcing, depending on the effect produced by specifying that the sequence of steps must first include the forced terms before considering the other terms, and on the effect of requiring the presence of the forced terms regardless of the sequence used. A forced term that would not otherwise be present because of a low F-ratio for its B_i usually has a relatively small B_i and, hence, little real effect, but the effect of specifying the initial sequence of steps may still be substantial.

In analyzing the engine test data, the linear terms (X_1-X_3) were forced into the regressions for the Plymouth engine, but no forcing was used for the Valiant, Chevrolet, and Ford engines. Forcing of linear terms improves the internal consistency of the equations for various speed/load cases. Where some dependency on linear terms is reasonably expected, forcing such terms gives greater confidence in any within-data interpolations or beyond-data extrapolations that may be necessary for prediction purposes. Finally, forcing of linears avoids certain unreasonably-shaped data-contour maps (see below) that occur when square or cross-product terms dominate the regression. Such maps, even if they describe the input data accurately, are not desirable as displays of functional relationships. For the Valiant, Chevrolet, and Ford, description of the data was a primary objective, and the advantages offered by forcing of linear terms were not felt to be sufficient to justify rerunning the regression analyses and carrying out new matrix-calculation and data-mapping operations. The tables included below show that most of the four equations for each speed/load case have at least two of the three linear variables present, even though forcing was not used. The regression equations for the Plymouth engine,

Engine	No. of Equations With Indicated No. of Linear Terms 3	2	1	0	Total No. of Equations
Valiant	17	10	5	0	32
Chevrolet	12	14	2	0	28
Ford	10	15	6	1	32
Plymouth[(a)]	28	18	9	1	56

	No. of Equations for Rel. NO_x With Ind. No. of Linear Terms 3	2	1	0	Total No. of NO_x Eqns.
Valiant	5	2	1	0	8
Chevrolet	6	1	0	0	7
Ford	6	2	0	0	8
Plymouth[(a)]	12	1	1	0	14

(a) Without linears forced.

without linears forced, are not significantly different in this respect from those for the other engines. But it was felt that the Plymouth equations should be as useful as possible in predicting vehicle operation that might lie, in part, outside the experimental data range. It was, therefore, felt to be preferable to force linear terms to appear in all Plymouth equations, and to prepare data-contour maps from these equations rather than those which lacked some linear terms. In fact, of the 56 Plymouth regression equations, forcing of linear terms changed 32 equations to some extent, but only 16 were changed substantially in the identity of terms and/or magnitude of the coefficients of terms.

The input data used for the regression analyses include all the engine test runs, both with and without recycle, except those in which misfire was recorded. This excluded, primarily, a few runs with lean carburetion and high recycle rates. The zero-recycle runs included those at manufacturer's specified A/F ratio and spark timing as well as any runs at other ratios and timing that were carried out as preliminary runs before use of recycle gas. Regression analyses were also computed in which only the runs with recycle were included. The resulting equations were usually more accurate in predicting the experimental results, than the regressions with zero-recycle, but the equations obtained were more often inconsistent between speed/load cases and sometimes gave unrealistic representations of the functional relationships. Extrapolation of these equations outside the actual data range often led to impossible conclusions.

Tables A2.1-A2.4 list the regression-equation coefficients for each equation for each speed/load case for each engine. The coefficients stated are those for regressions which included zero-recycle runs in the input. For the Plymouth engine, the linear terms (X_1-X_3) are forced to appear in the regression. The tables include the standard deviation of the input data (% relative emission yields and relative BSFC), the % of the data variance explained by the regression, and the residual standard deviation of the data about the regression function. The latter is a measure of the accuracy with which the regression describes the ratio of observed emissions or BSFC relative to base. Thus, a residual standard deviation of 0.02 for Y, in a given engine and speed/load case means that 95% of the observed relative NO yields (base = 1.00) will lie within ± 0.04 of the values computed from the regression equation. The tables also list the number of test runs (data cards) correlated in each regression. The greater this number, the more confidence may be held in the predictions of the equations. The Data-Limit Charts, included with the Data-Contour Maps and discussed below, show the values of the variables examined in the engine tests at each speed/load case. Use of the regression equations outside of the experimental data range, i.e., extrapolation, can be misleading even where the equation describes the experimental data accurately.

113

[illegible]

A2.2 Matrix Calculation and Data Mapping

For each speed/load case, 5 values each of A/F ratio, spark timing, and % recycle are selected to bracket the experimental data. These values, suitably transformed to yield X_1-X_3 values, provide 125 points of a 3-dimensional matrix. The four regression equations (Y_1-Y_4) are solved for each point of the matrix, yielding 125 solutions for each of the 4 dependent variables, stated as relative emissions or BSFC, compared to the manufacturer's base values.

At selected A/F ratio levels in the matrix, contour maps are drawn for relative-yield levels at various values of spark timing and % recycle. The contour lines (4 sets, for 4 variables at each A/F) are defined by interpolation from the regression-equation solutions of the matrix points. The variable levels mapped are chosen to match the experimental levels as nearly as possible. Usually, 3 levels of A/F ratio are mapped except where data were restricted to only 2 levels.

The resulting Data-Contour Maps for each speed/load case and engine are included in Figs. A2.5-A2.142. Preceding each set of 2 or 3 maps for a speed/load case is a Data-Limit Chart showing the experimental range studied. The spark timing values shown are usually the MBT timing. In addition, tests were run at 5 and 10-degree retards from the chart values. The Limit Charts and Maps also include the mass emission and BSFC rates and pollutant concentrations under manufacturer's base conditions, as well as the speed, torque, air rate, A/F ratio, IMAP, and spark timing characteristic of the speed/load case. In some maps, the contours for computed values of the dependent variables are shown in only a portion of the map field; the unmapped portions lie outside the experimental range. Any contours in such areas would be of limited validity. Since tests in which misfire was recorded (usually, lean A/F and high recycle) were excluded from the regression equations, contours drawn in such areas also do not accurately describe the data obtained.

In mapping data from the Plymouth engine, relative yields of CO are shown only on the 14.5 A/F ratio maps. Relative yields for 15.5 (near base conditions) and 16.5 ratios are low and show little variation in relation to the accuracy of the regression equations.

The Contour maps, Data-Limit Charts, and their associated numerical entries, together with the tables of regression-equation coefficients, provide the best available method of presenting the data in usable form. Each of the four dependent variables is displayed separately as a function of the three independent variables. A further very useful simplification would be the combination of the four dependent variables into a single "objective" function whose minimum value would represent the optimum combination of the three independent variables. This function might involve the minimum yield of NO and the minimum deviations, from base values, of the CO and HC yields and BSFC. In combining the NO_x yield and the deviations, however, weighting coefficients are required to assign relative importances to the four variables, i.e., to specify, for example, how much fuel-economy penalty is acceptable for a given NO reduction, etc. Any such decisions are essentially subjective, however, and for this reason none of the calculated objective functions for the various engines and speed/load cases was ultimately accepted for use and none is presented in this report.

A-11

DATA FOR PLYMOUTH

FIGURE A2.5

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

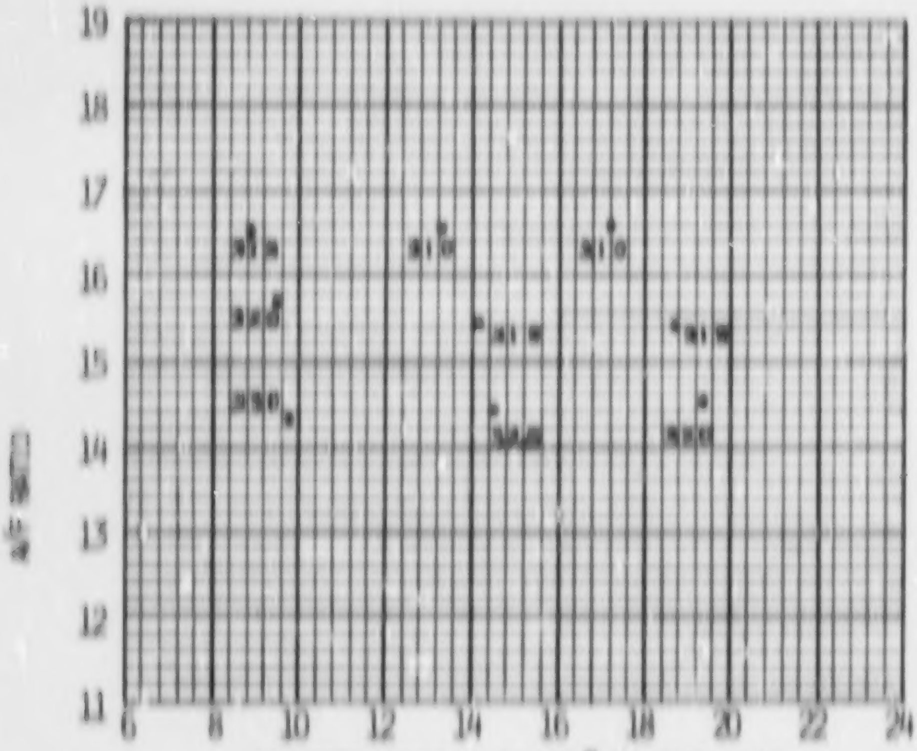
ENGINE: Plymouth RPM: 1500 LB.-FT. TQ. 50

MFR'S A/F: 15.5/1 MFR'S. SPARK: 323 IMAP(1) 11.0-11.5 "HG.

CARB. AIR RATE(1) 4.33 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle
A/F 14.5-16.5
Spk. 323

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.6

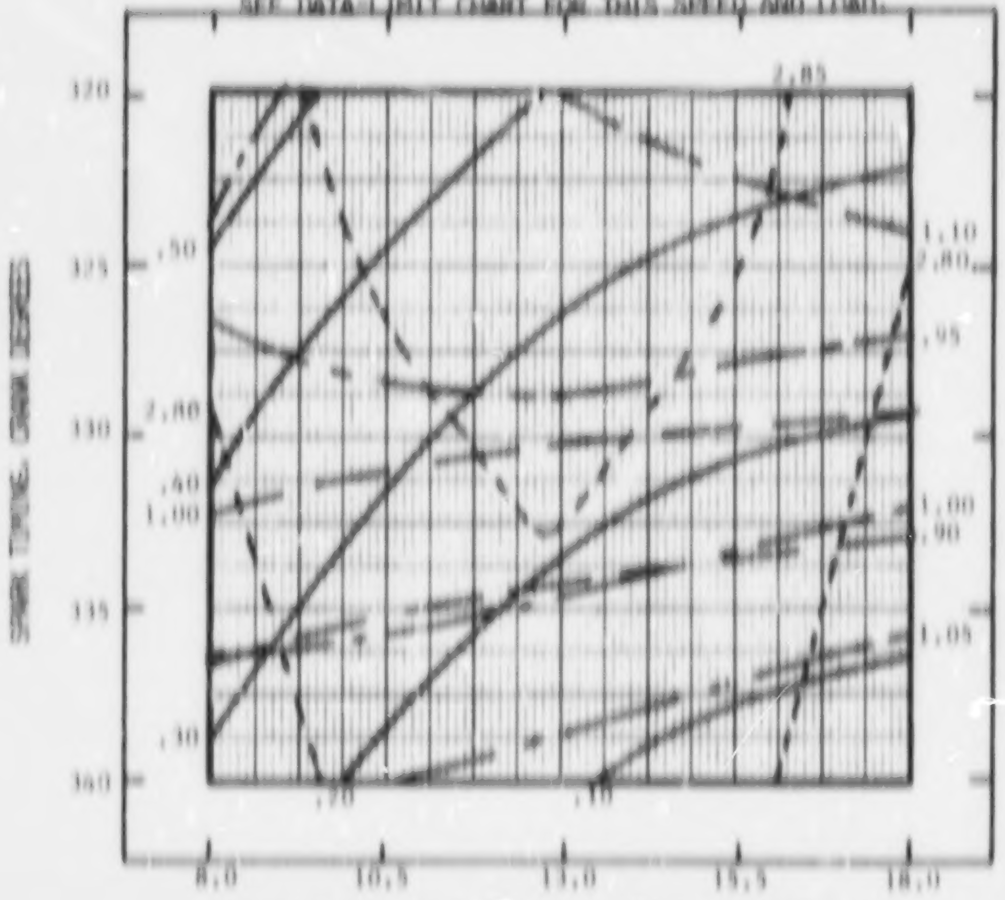
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-H A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.6036	2763 PPM NO	98.0
REL. # UBHC/HR. (FID)	▭ ▭ ▭ ▭	0.6336	1082 PPM C6	88.9
REL. # CO/HR.	▫▫▫▫▫▫▫	0.5177	0.39 %	98.0
REL. # FUEL/BHPHR.	▪ ━ ▪	0.7256		83.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

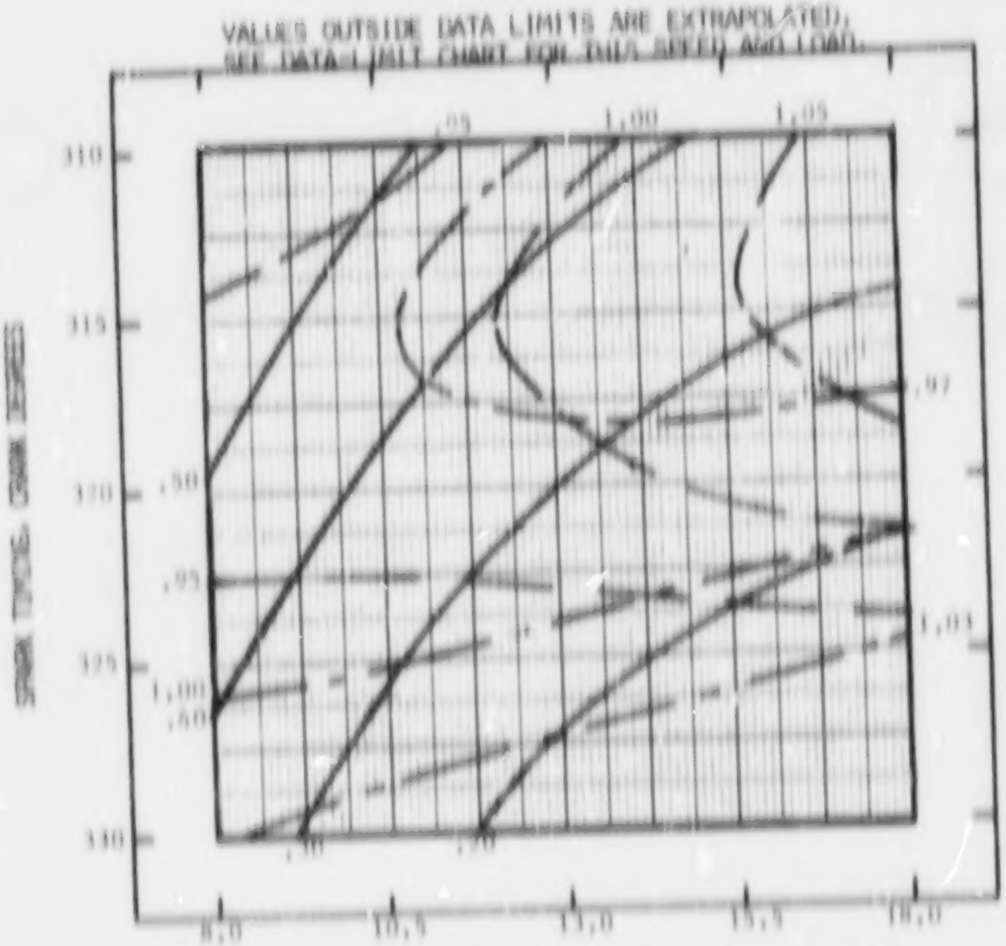
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.7

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-M A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬ ▬▬	0.6036	2763 PPM NO	98.0
REL. # C6HC/HR. (FID)	- - - -	0.6336	1082 PPM C6	88.9
REL. # CO/HR. (Not plotted)	-------	0.5177	0.39 %	98.0
REL. # FUEL/BHPHR.	- — -	0.7256		83.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

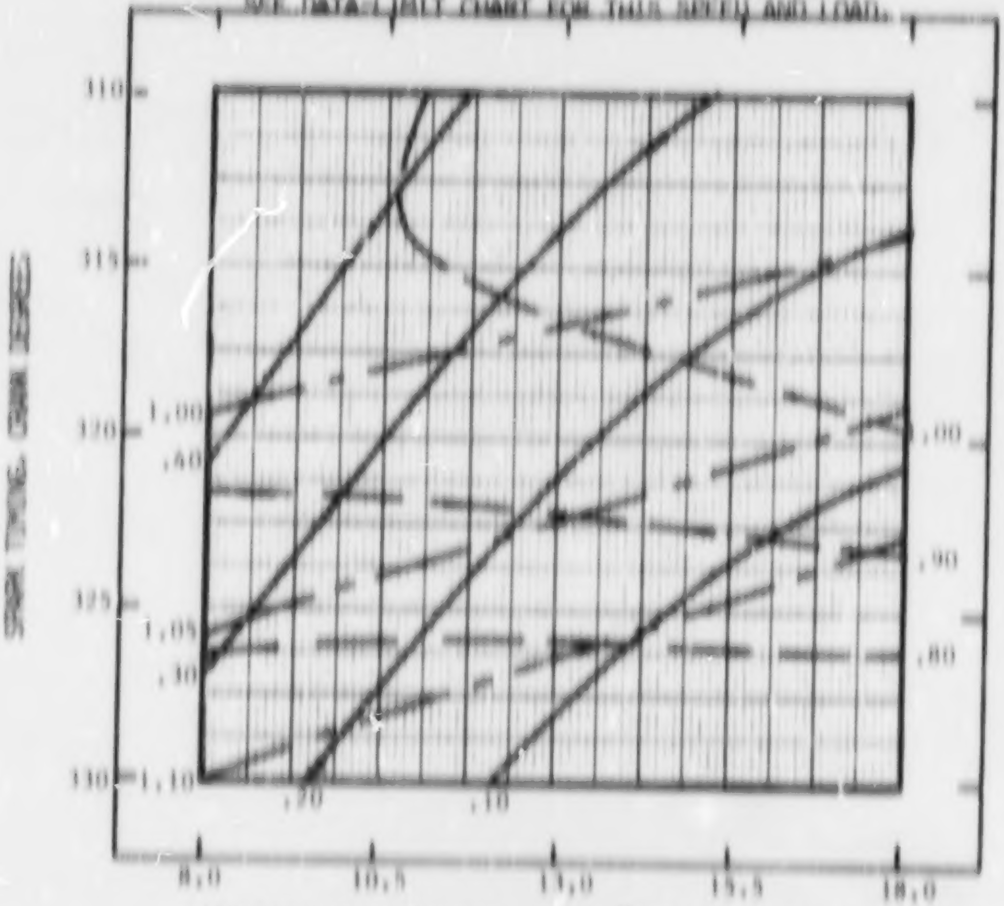
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.8

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1300
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN
REL. # NO2/HR.	———	0.6036	2263 PPM NO	98.0
REL. # C6HC/HR. (FID)	= = = =	0.5336	1082 PPM C6	88.9
REL. # CO/HR. (Not Plotted)	--- ---	0.3172	0.39 %	98.0
REL. # FUEL/BHPHR.	= —— =	0.7256		83.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK. NO RECYCLE. CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.9

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

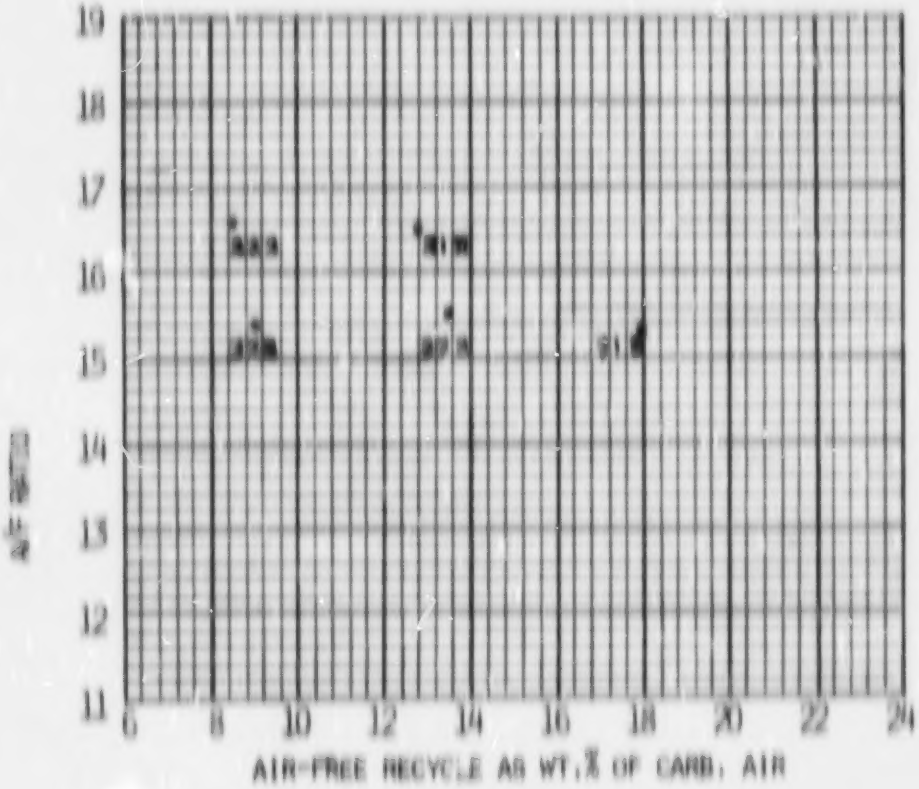
ENGINE: Plymouth RPM: 1500 LB.-FT. TQ. 75

MFR'S A/F: 15.4/1 MFR'S. SPARK: 12° IMAP(1) 11.7-11.9"HG.

CARB. AIR RATE(1) 3.28 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 15.4 - 16.4
Spk. 12°

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

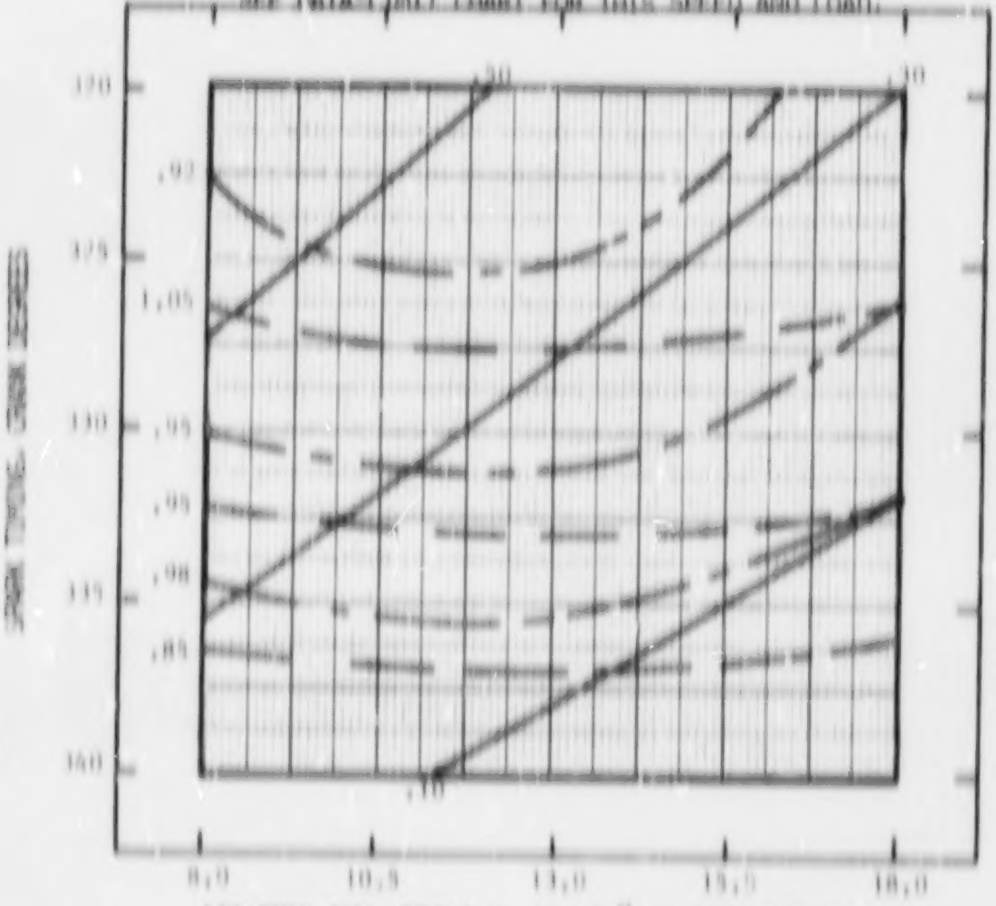
(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A7.10

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	1500
CID	318	LB.-FT. TORQUE(1)	75
CONTROL SYSTEM	SH	A/F RATIO(2)	15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



No data obtained near 14.5 A/F.

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.1625	4070 PPM NO	99.7
REL. # C6HC/HR. (FID)	▪ ▪ ▪ ▪	0.5312	1039 PPM C6	97.9
REL. # CO/HR. (Not Plotted)	┅┅┅┅	0.6575	0.38 %	95.7
REL. # FUEL/BHPHR.	▪ ━ ▪	0.6258		90.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A-1.11

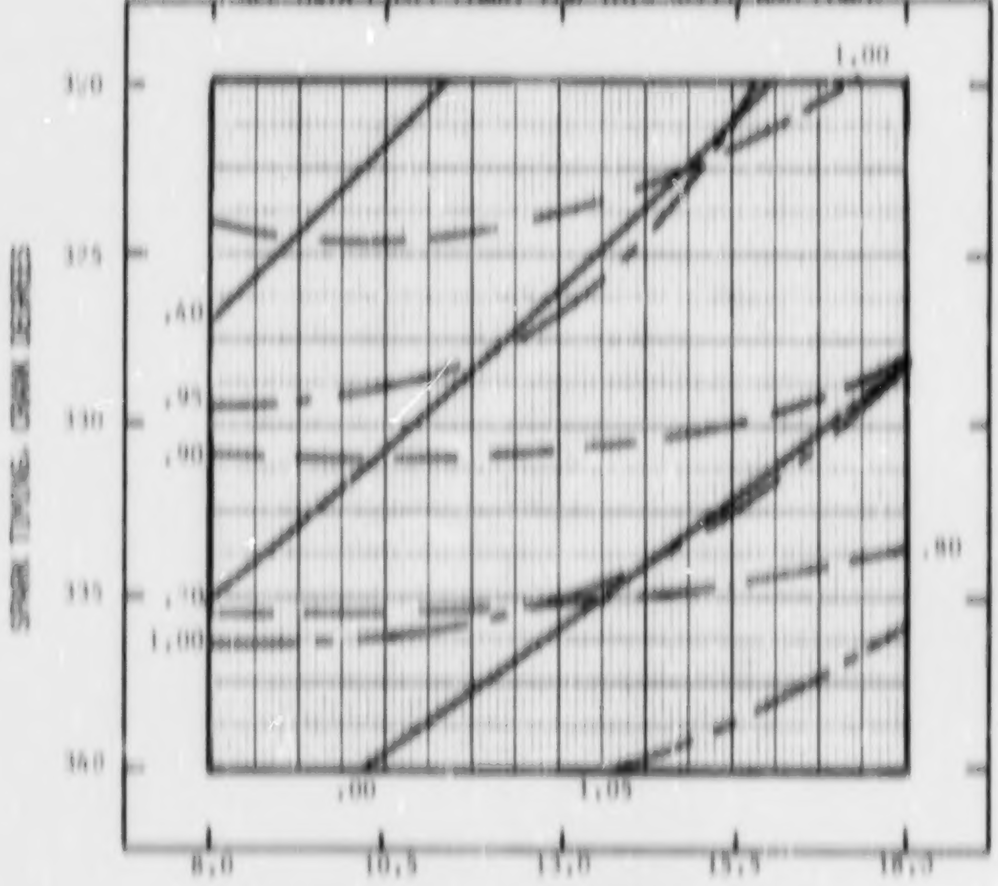
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	1500
CID	318	LB.-FT. TORQUE(1)	75
CONTROL SYSTEM	E-M	A/F RATIO(2)	16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.1625	6070 PPM NO	99.7
REL. # C6HC/HR. (FID)	= = = =	0.5312	1039 PPM C6	97.8
REL. # CO/HR. (Not Plotted)	-------	0.6575	0.38 %	95.7
REL. # FUEL/BHPHR.	═ ══ ═	0.6248		90.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Homograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.12

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

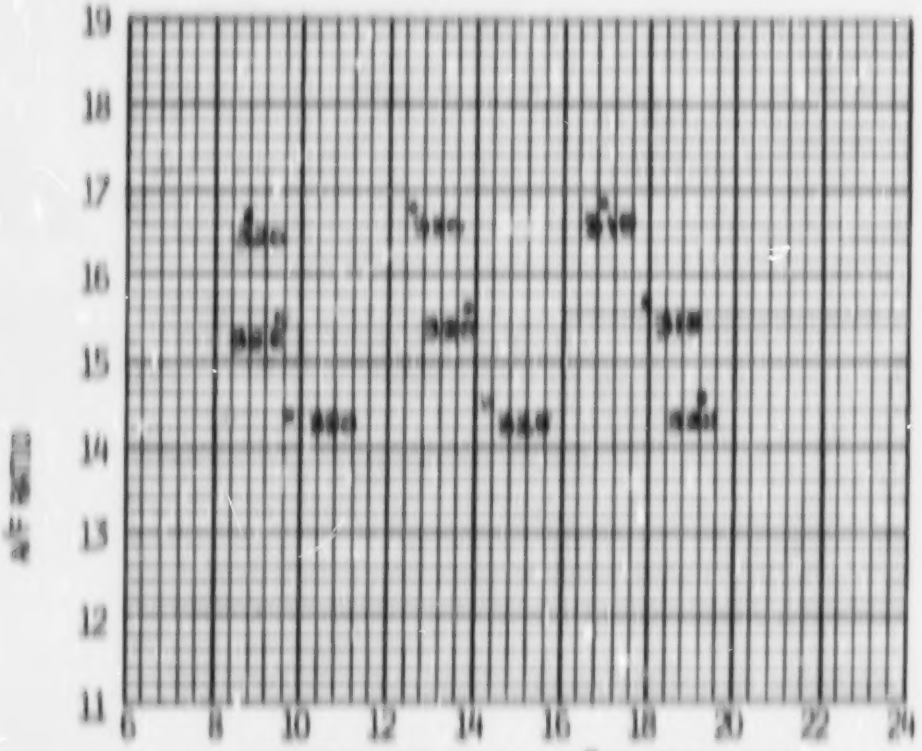
ENGINE: Plymouth RPM: 1500 LB.-FT. TQ. 100

MFR'S A/F: 15.6/1 MFR'S. SPARK: 10 IMAP(1) 15.8-16.3 "HG.

CARB. AIR RATE(1) 1.85 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



AIR-FREE RECYCLE AS WT.% OF CARB. AIR

Data For
Zero Recycle
A/F 15.3 - 16
Spk. 10

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.13

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

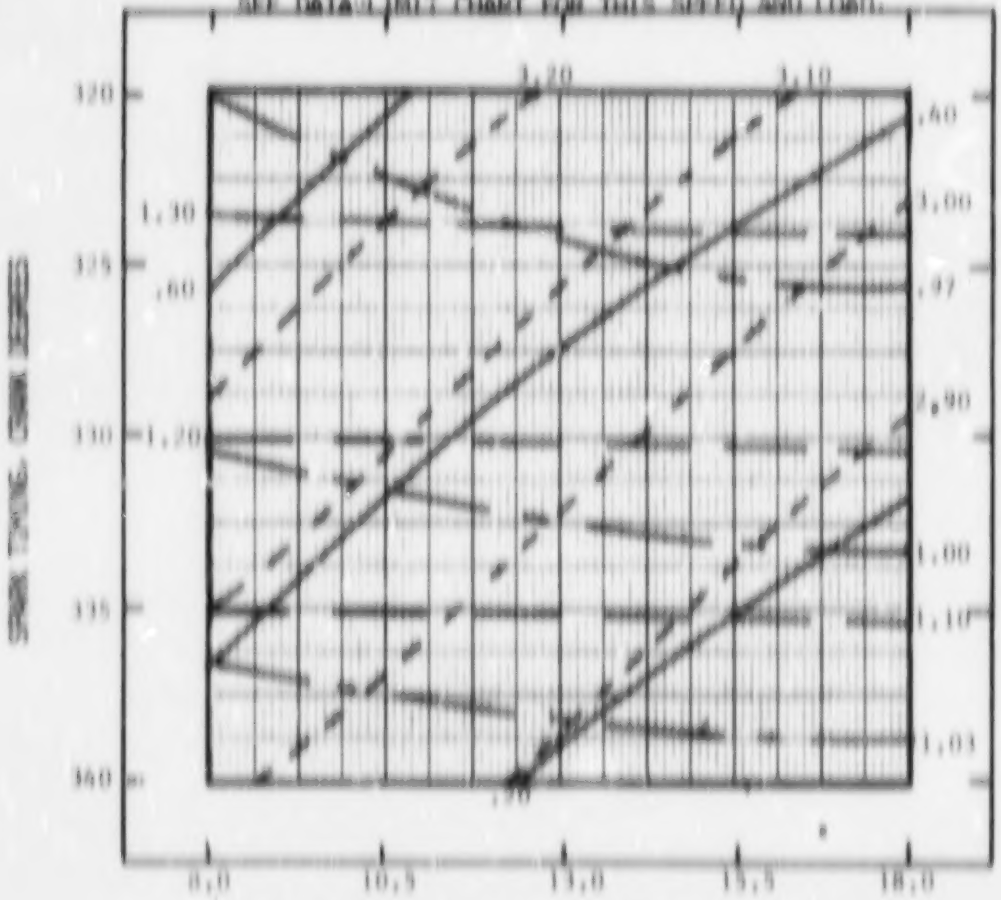
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500

CID 318 LB.-FT. TORQUE(1) 100

CONTROL SYSTEM E-H A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1,3338	6057 PPM NO	97,8
REL. # C6HC/HR. (FID)	= = = =	0,6636	776 PPM C6	95,5
REL. # CO/HR.	·······	0,6588	0,21 %	97,6
REL. # FUEL/BHPHR.	= — =	0,5379		95,2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.16

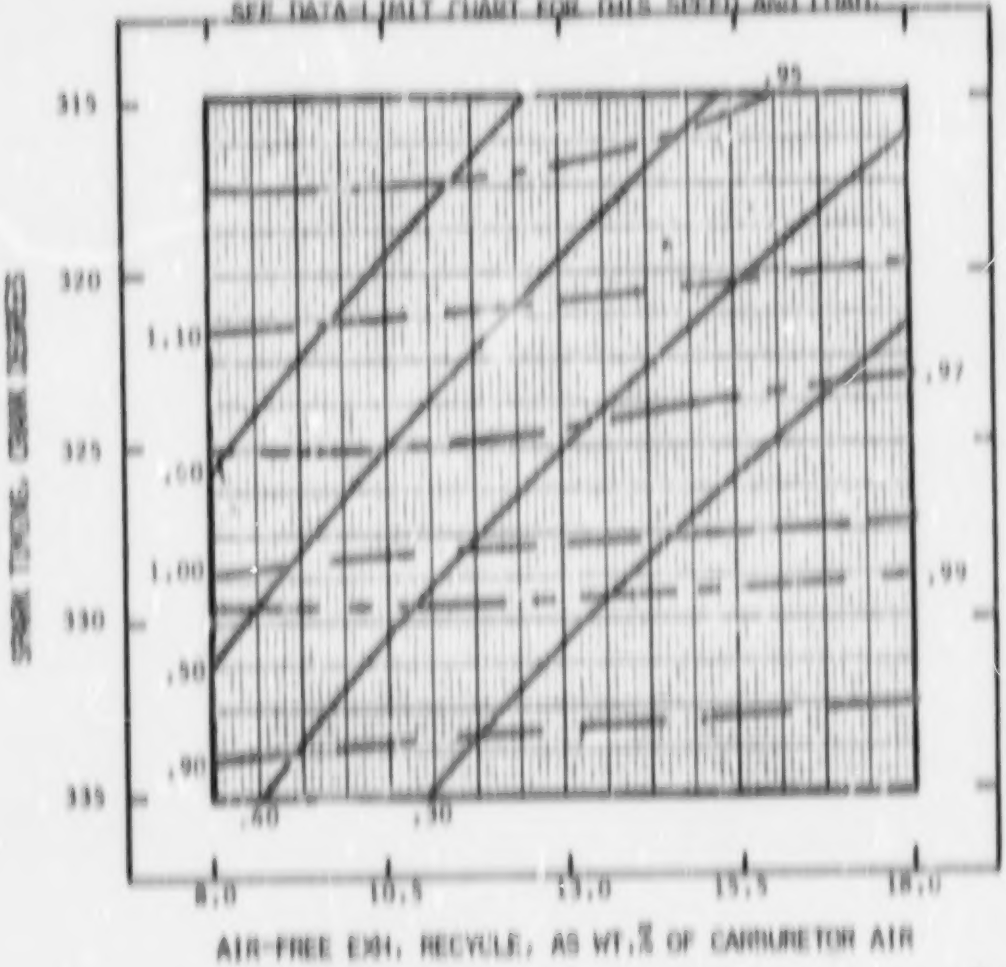
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-H A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.3318	6057. PPM NO	97.8
REL. # C6E/HR. (FID)	▭ ▭ ▭ ▭	0.6836	778 PPM C6	95.5
REL. # CO/HR. (Not Plotted)	-------	0.4388	0.73 %	97.6
REL. # FUEL/BHPHR.	▭ ━ ▭	0.5379		95.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.13

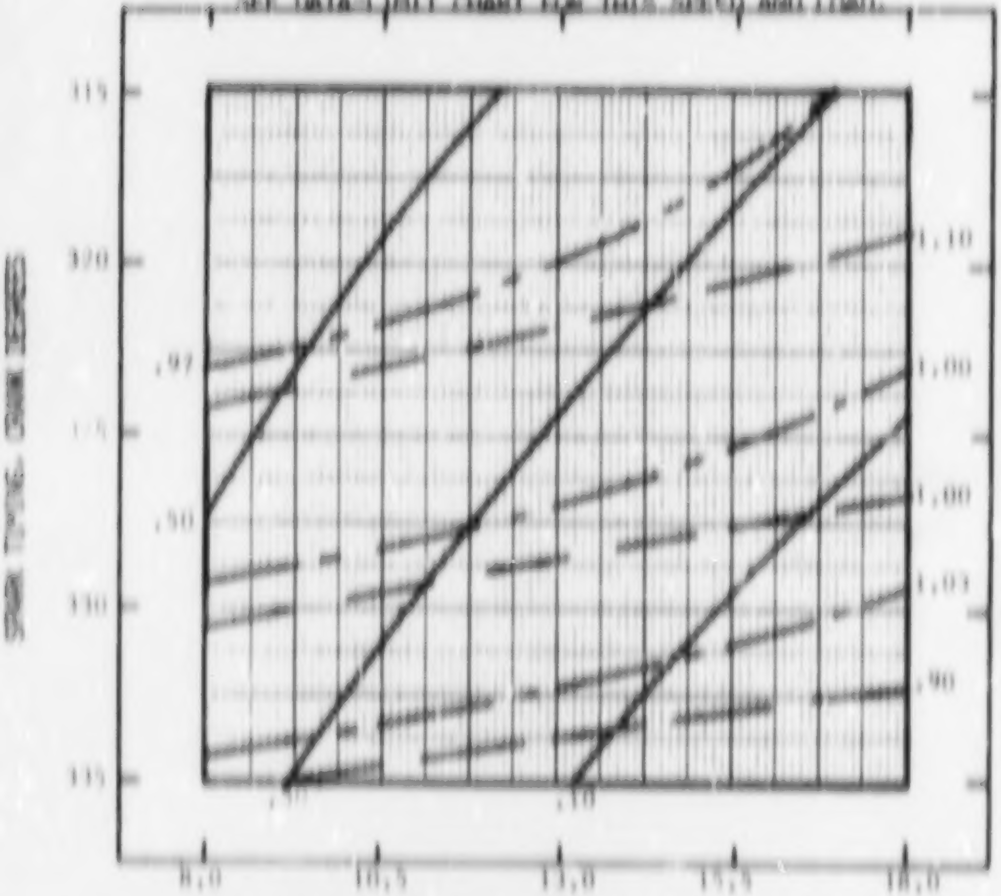
USING EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3338	6057 PPM NO	97.8
REL. # C_6HC/HR. (FID)	- - - -	0.6636	776 PPM C_6	96.5
REL. # CO/HR. (Not Plotted)	·······	0.6588	0.23 %	97.6
REL. # FUEL/BHPHR.	- — -	0.5379		95.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.16

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

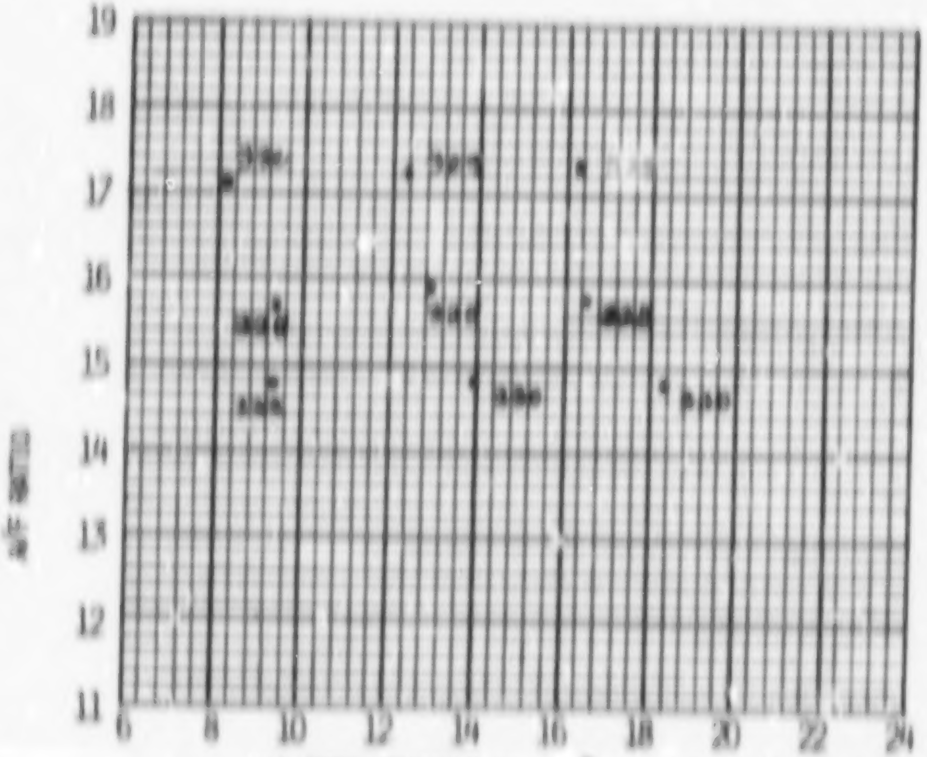
ENGINE: Plymouth RPM: 1500 LB.-FT. TQ. 140

MFR'S A/F: 15.3 MFR'S. SPARK: 142 IMAP(1) 19.5-19.8 "HG.

CARB. AIR RATE(1) 4.82 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle
A/F 16.3 - 16.5
Spk. 360-353

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.17

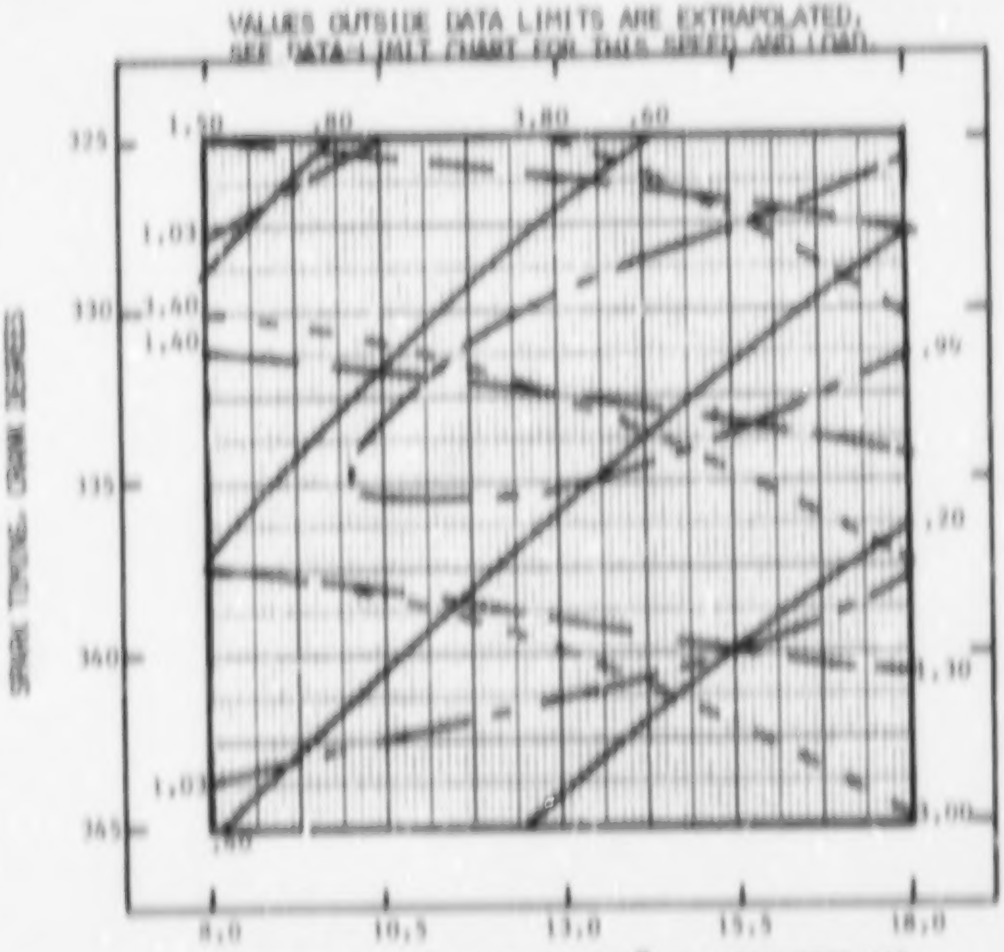
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 160
CONTROL SYSTEM EM A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3207	3183 PPM NO	96.9
REL. # C6/C/HR. (FID)	– – – –	0.6960	837 PPM C6	73.5
REL. # CO/HR.	·······	3.7683	0.31 %	97.6
REL. # FUEL/BHPHR.	– · –	0.6868		96.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A2.18

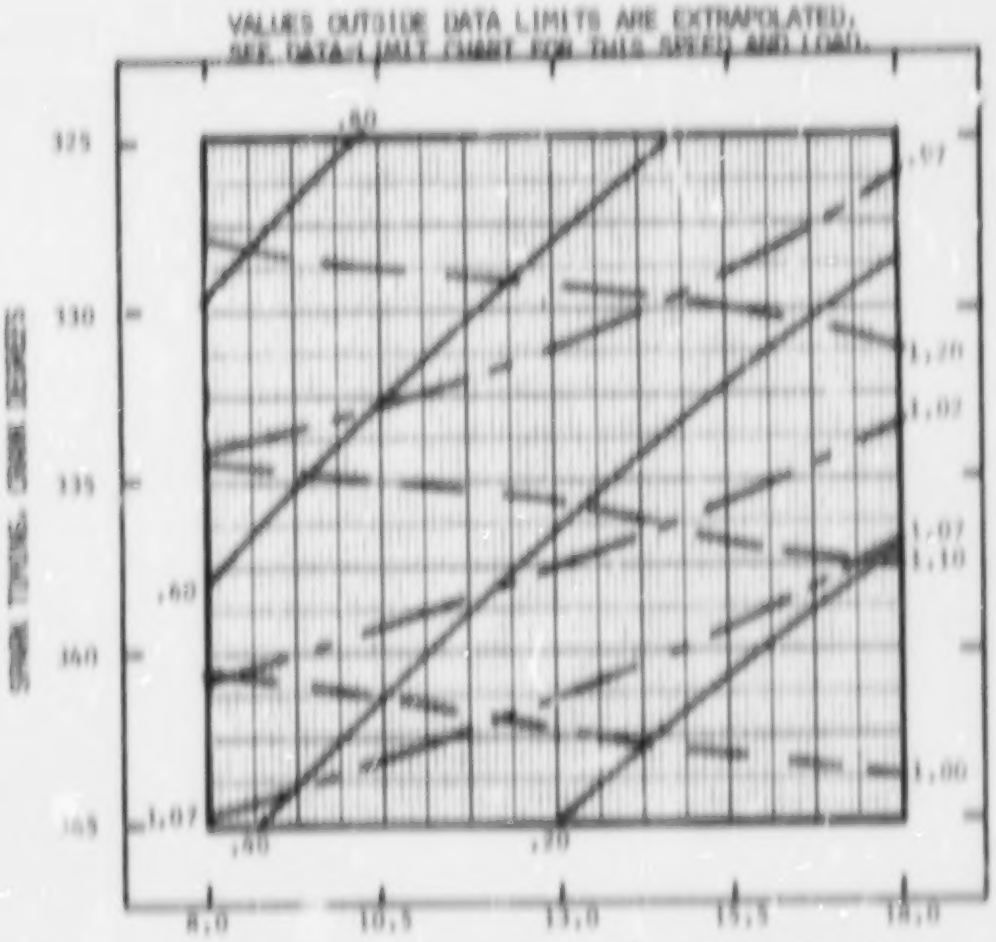
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	1500
CID	318	LB.-FT. TORQUE(1)	160
CONTROL SYSTEM	E-II	A/F RATIO(2)	15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.3707	3181 PPM NO	98.9
REL. # C6/HC/HR. (FID)	▭ ▭ ▭ ▭	0.4958	673 PPM C6	73.5
REL. # CO/HR. (Not Plotted)	▬▬▬▬▬	0.7683	0.31 %	97.6
REL. # FUEL/BHPHR.	▬ ━━ ▬	0.6848		99.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL.: Leonard Nomograph

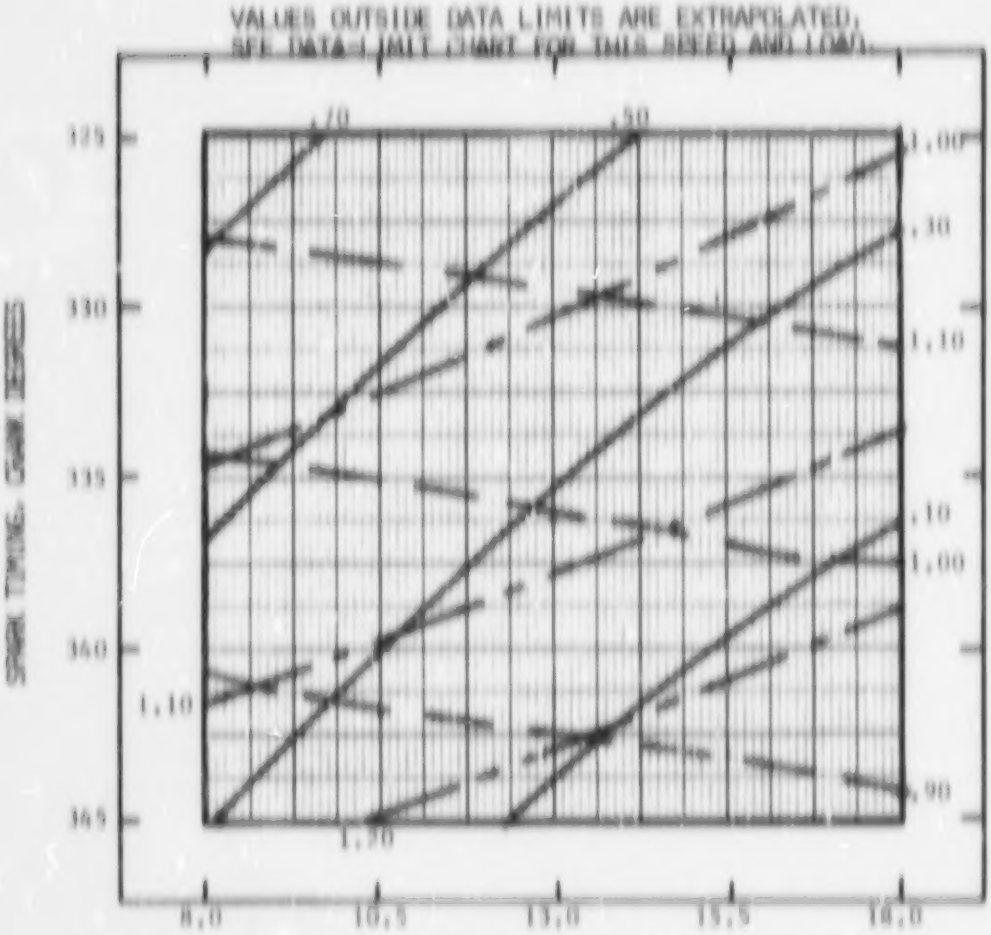
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.19

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 1500
CID 318 LB.-FT. TORQUE(1) 150
CONTROL SYSTEM E-H A/F RATIO(2) 16.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3207	3183	PPM NO	96.9
REL. # UHC/HR. (FID)	- - - -	0.4940	657	PPM C6	73.5
REL. # CO/HR. (Not Plotted)	--------	0.7685	0.31	%	97.6
REL. # FUEL/BHPHR.	- — -	0.6868			96.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MHR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.20

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

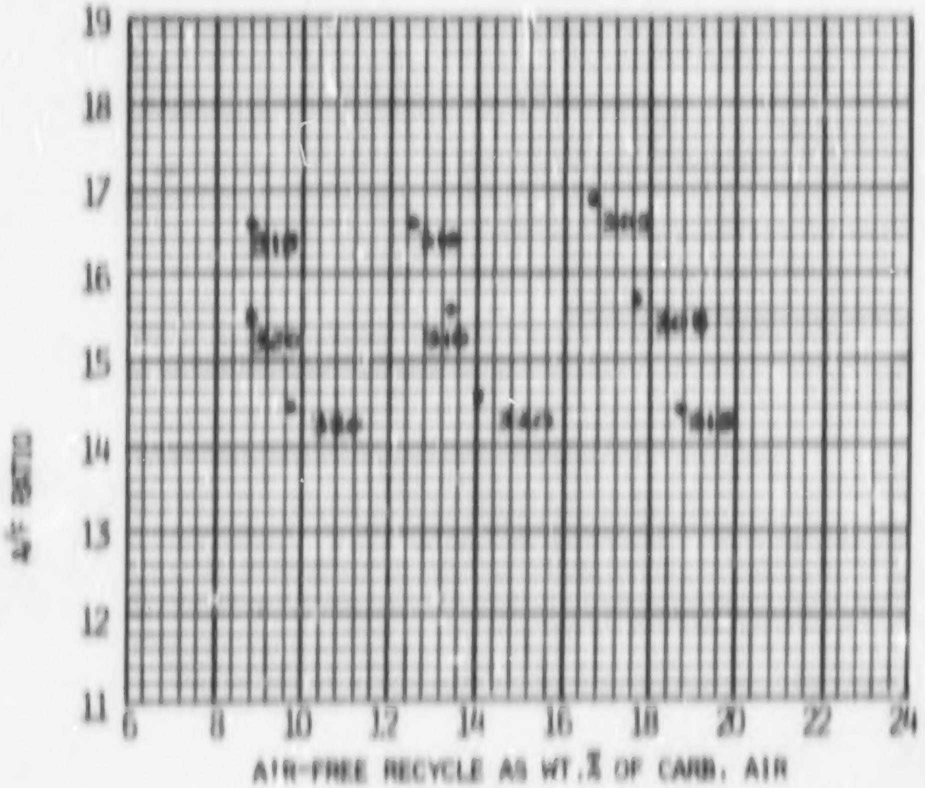
ENGINE: Plymouth RPM: 2000 LB.-FT. TQ. 50

MFR'S A/F: 15.6/1 MFR'S. SPARK: 120 IMAP(1) 11.1-11.6 "HG.

CARB. AIR RATE(1) 1.66 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 14.6 - 16.6
Spk. 120

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.21

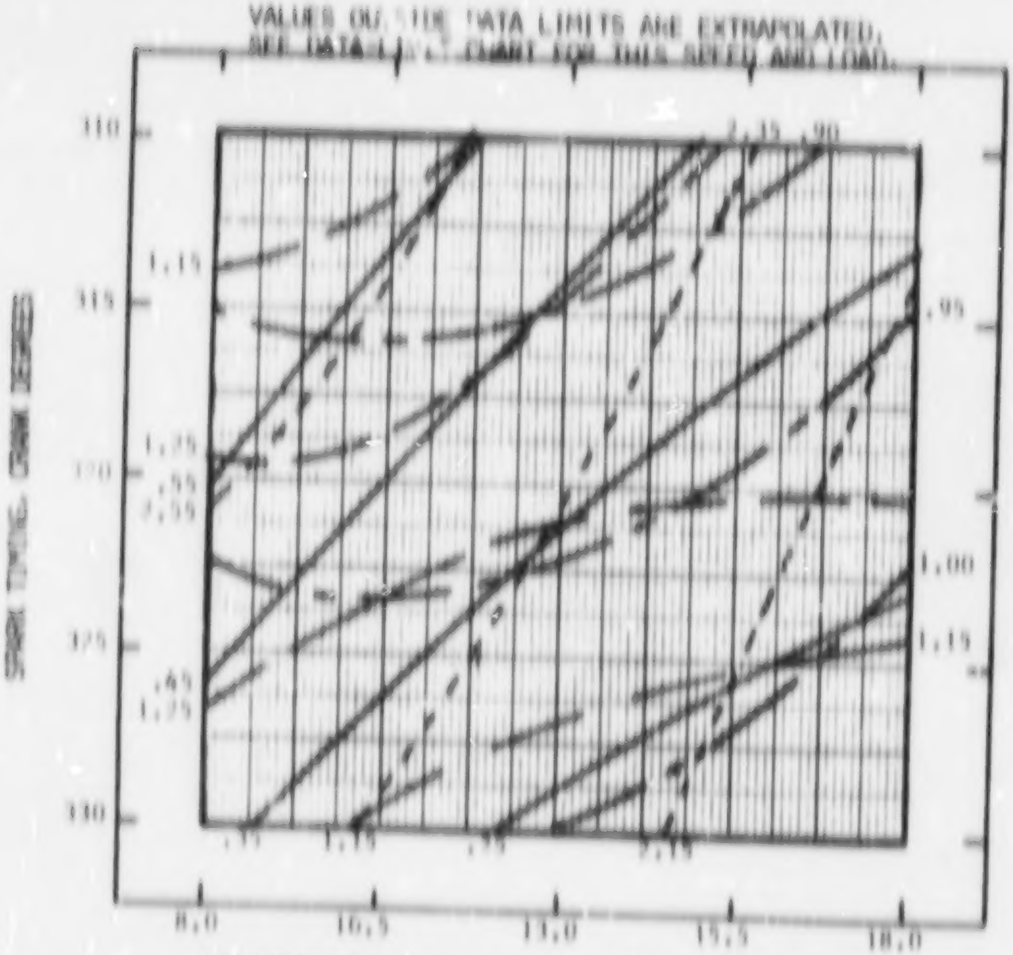
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-M A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	——	0.9761	1516 PPM NO	98.1
REL. # C6HC/HR. (FID)	- - - -	0.6175	779 PPM C6	93.1
REL. # CO/HR.	·······	0.6730	0.38 %	97.5
REL. # FUEL/BHPHR.	- — -	0.7273		91.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Jacuard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.77

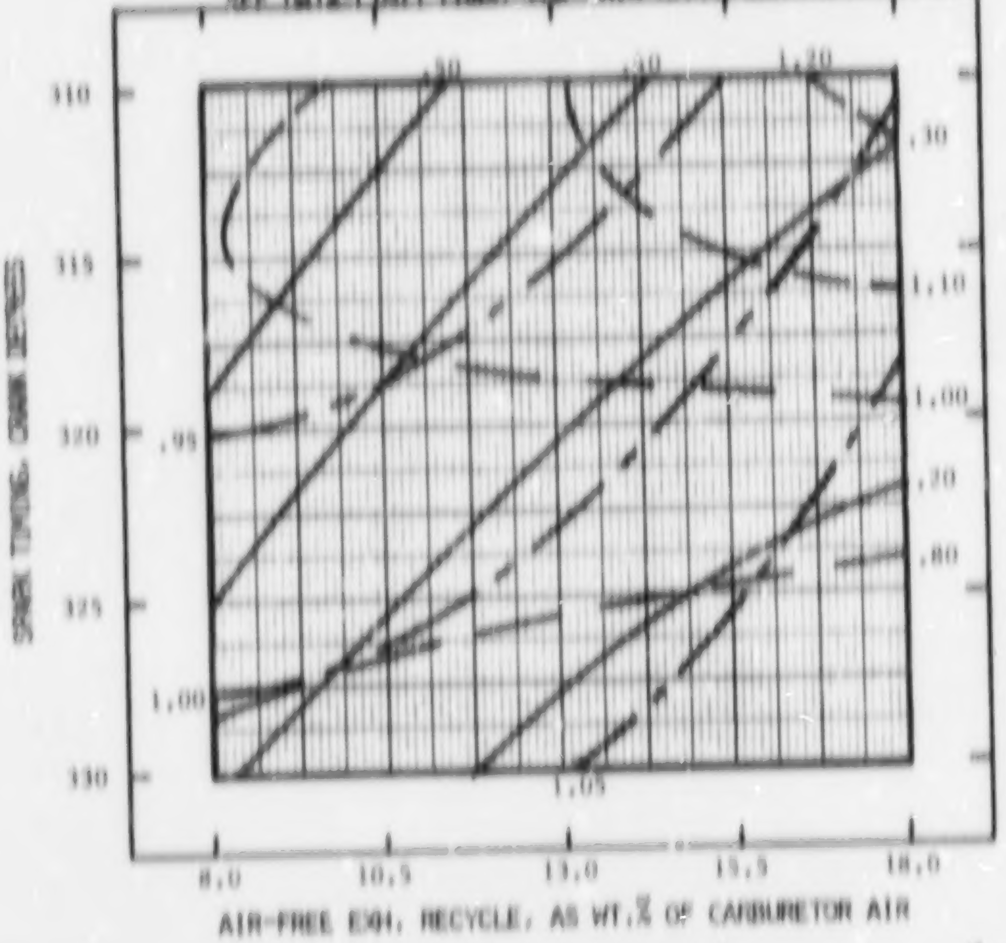
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-H A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.9761	1316 PPM NO	98.1
REL. # C6/HC/HR. (FID)	— — — —	0.6175	779 PPM C6	93.1
REL. # CO/HR. (Not Plotted)	-------	0.6738	0.38 %	97.5
REL. # FUEL/BHPHR.	○ ▬ ○	0.7273		91.5

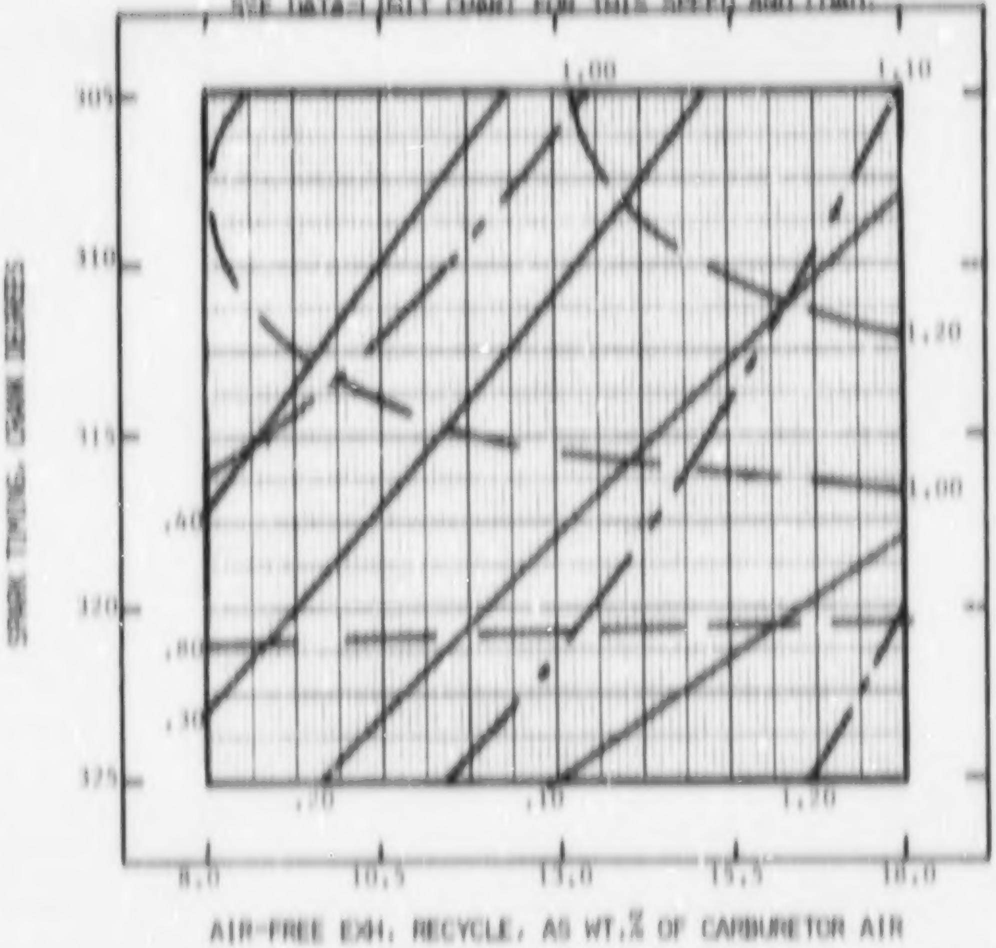
(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.23

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2000
CID	318	LB.-FT. TORQUE(1)	50
CONTROL SYSTEM	E-II	A/F RATIO(2)	16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.9761	3316 PPM NO	98.1
REL. # C6HE/HR. (FID)	– – – –	0.6173	779 PPM C6	93.1
REL. # CO/HR. (Not Plotted)	········	0.6738	0.38 %	97.5
REL. # FUEL/BHPHR.	– —— –	0.7273		91.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.34

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

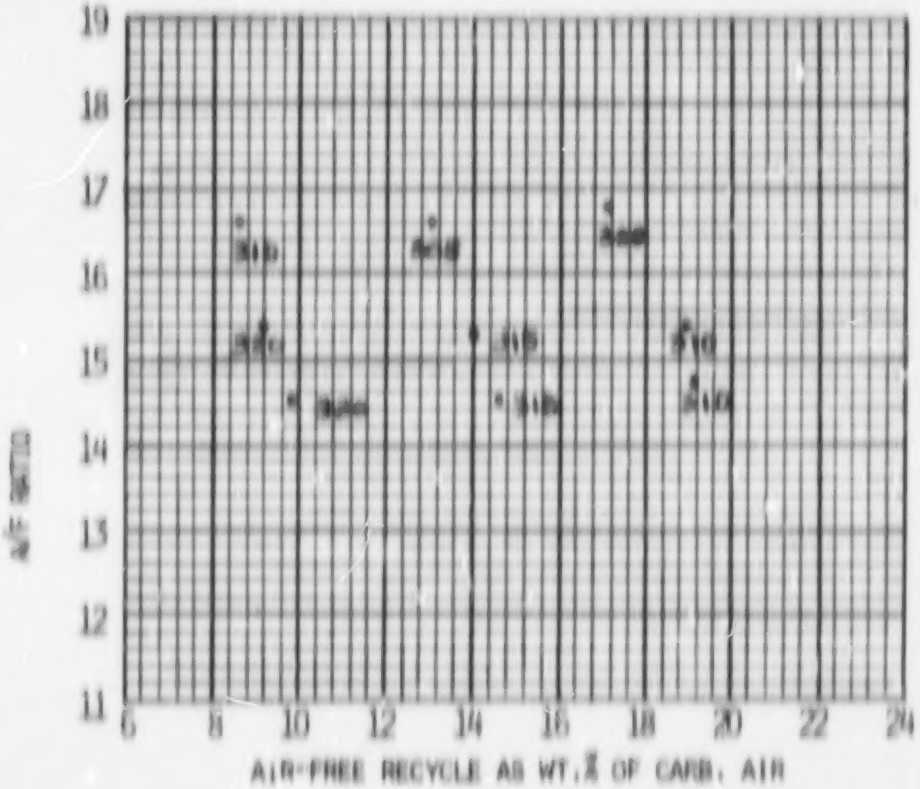
ENGINE: Plymouth RPM: 2000 LB.-FT. TQ. 75

MFR'S A/F: 15.5/1 MFR'S. SPARK: 320 IMAP(1) 13.4-13.8 "HG.

CARB. AIR RATE(1) 4.29 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 14.3 = 16/6
Spk. 320

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.25

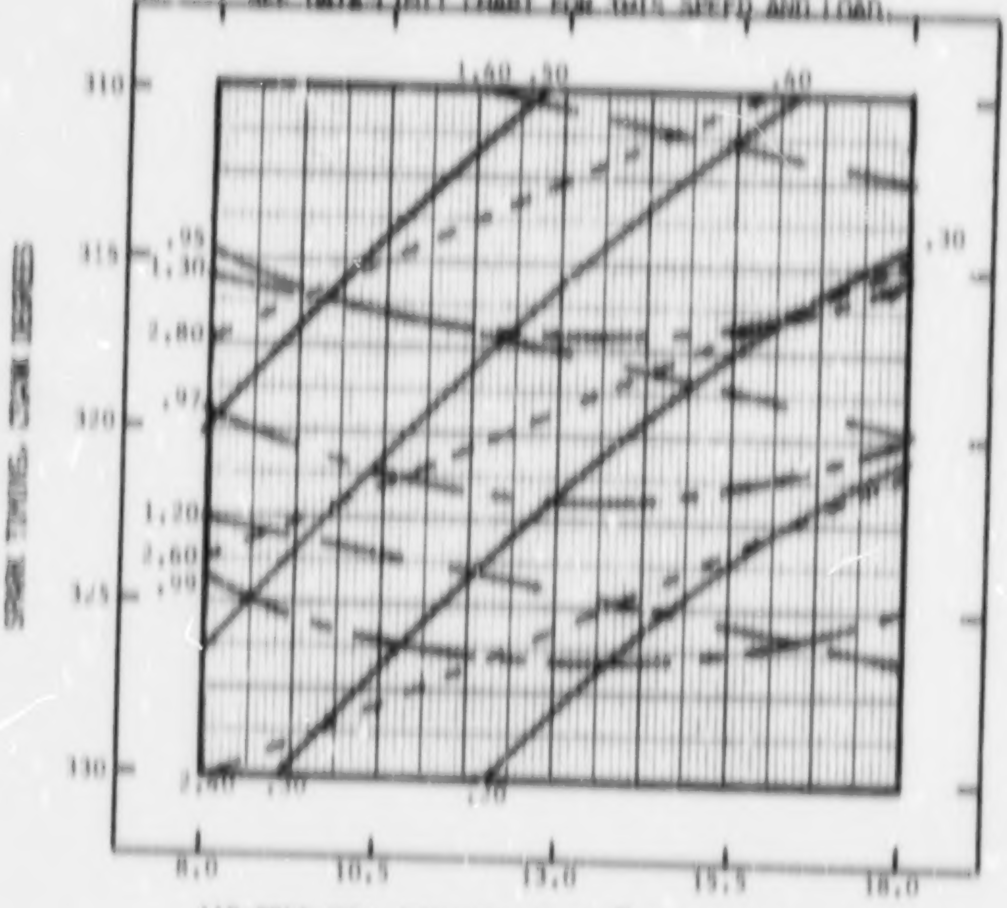
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM E-H A/F RATIO(2) 14.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6311	3873 PPM NO	97.9
REL. # C6HC/HR. (FID)	- - - -	0.5232	782 PPM C6	95.0
REL. # CO/HR.	-------	0.7086	0.32 %	97.8
REL. # FUEL/BHPHR.	— — —	0.6122		88.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.26

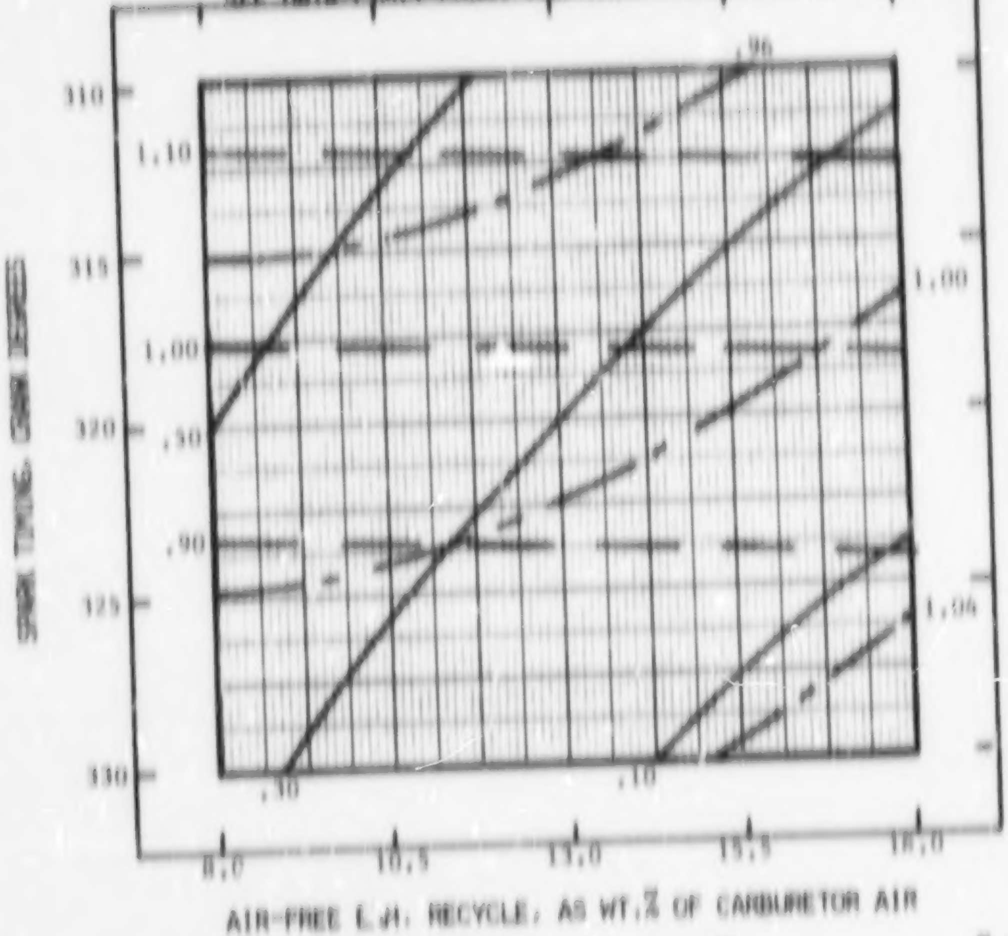
U.PHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM E-H A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬▬	1.6311	1875 PPM NO	97.9
REL. # C6/C/HR. (FID)	— — · —	0.5737	782 PPM C6	95.0
REL. # CO/HR. (Not Plotted)	- - - - -	0.7086	0.32 %	97.8
REL. # FUEL/BHPHR.	— —— —	0.6122		88.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.27

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

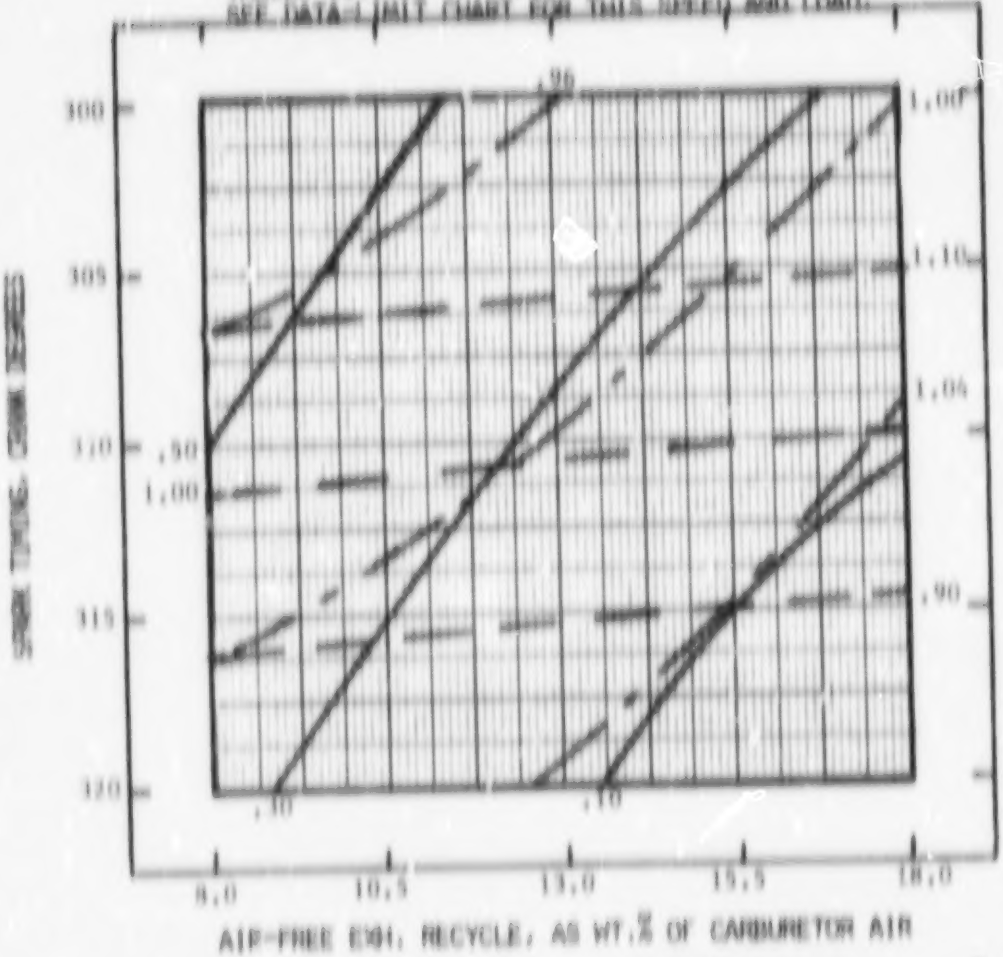
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000

CID ______ LB.-FT. TORQUE(1) 11

CONTROL SYSTEM ______ A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6311	3875 PPM NO	97.9
REL. # C6HC/HR. (FID)	– – – –	0.5232	782 PPM C6	95.0
REL. # CO/HR. (Not Plotted)	-------	0.7084	0.32 %	97.8
REL. # FUEL/BHPHR.	– — –	0.6122		88.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.78

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

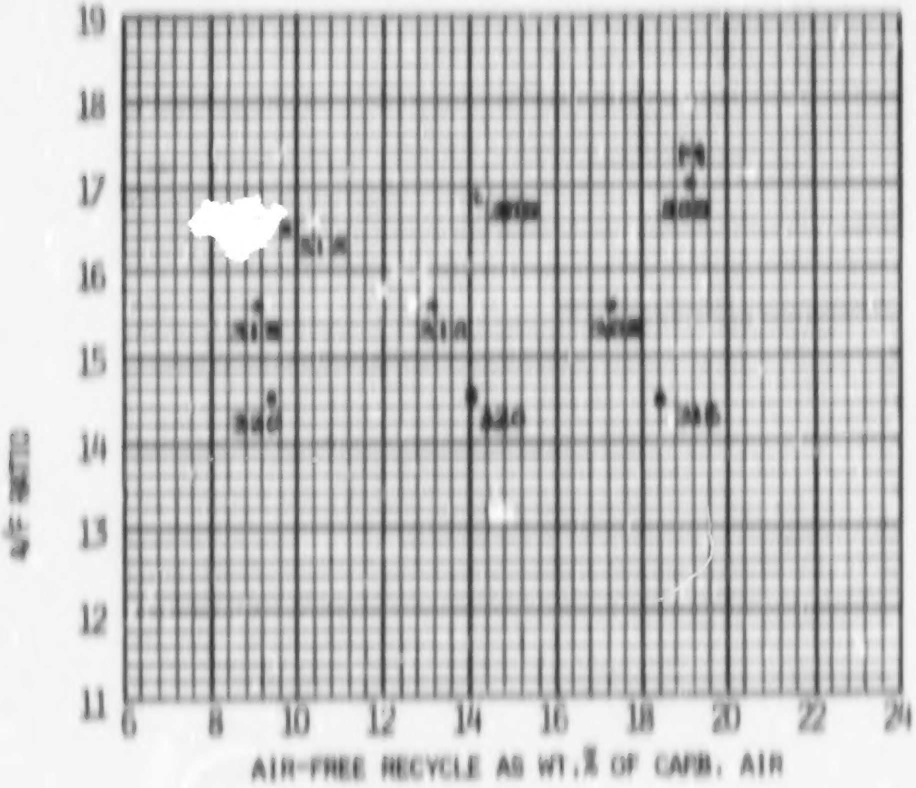
ENGINE: Plymouth RPM: 2000 LB.-FT. TQ. 100

MFR'S A/F: 15.5/1 MFR'S. SPARK: 32S IMAP(1) 15.3-15.6"HG.

CARB. AIR RATE(1) 3.13 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle
A/F 14.3 + 16.6
Spk. 32A + 32B

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.29

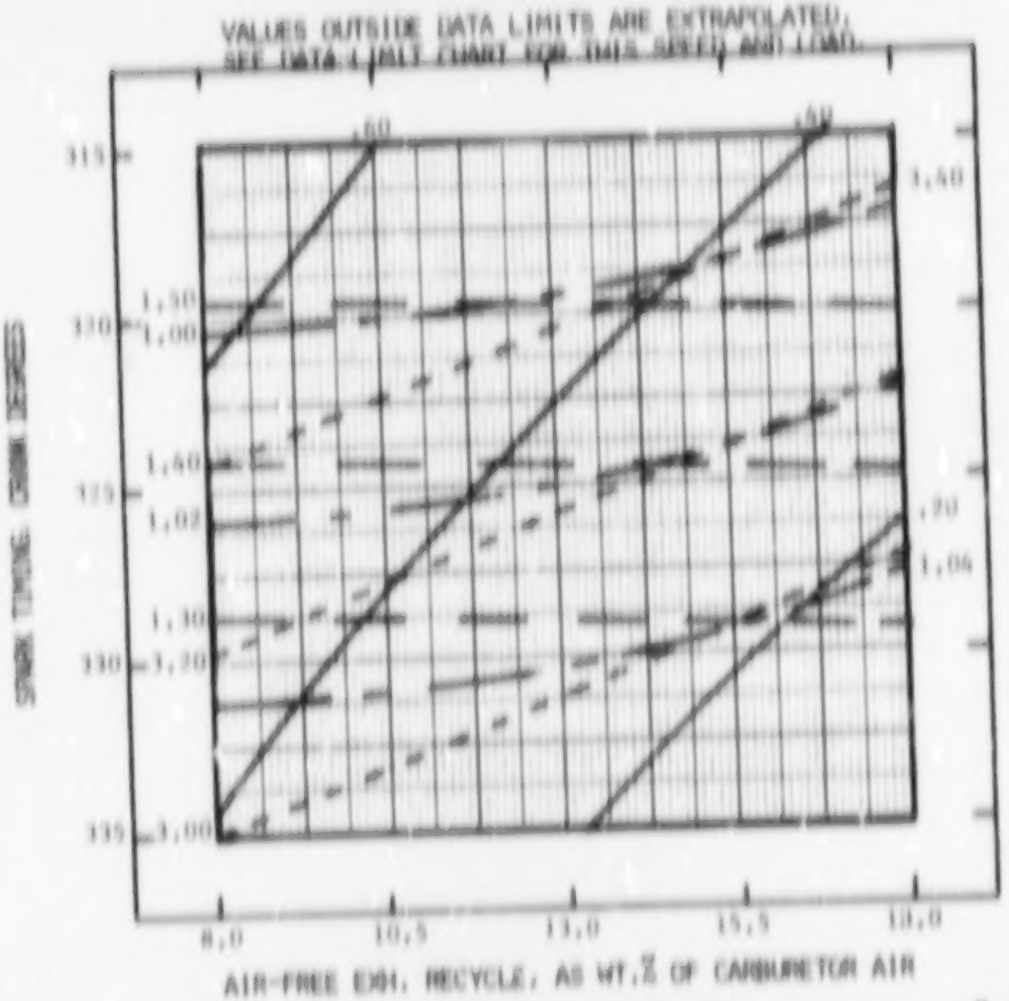
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth	ENGINE RPM 2000
CID 318	LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-R	A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.7618	1965 PPM NO	98.8
REL. # C6HC/HR. (FID)	— — — —	0.3935	490 PPM C6	88.6
REL. # CO/HR.	--------	0.6516	0.26 %	98.6
REL. # FUEL/BHPHR.	— —— —	0.5388		75.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.50

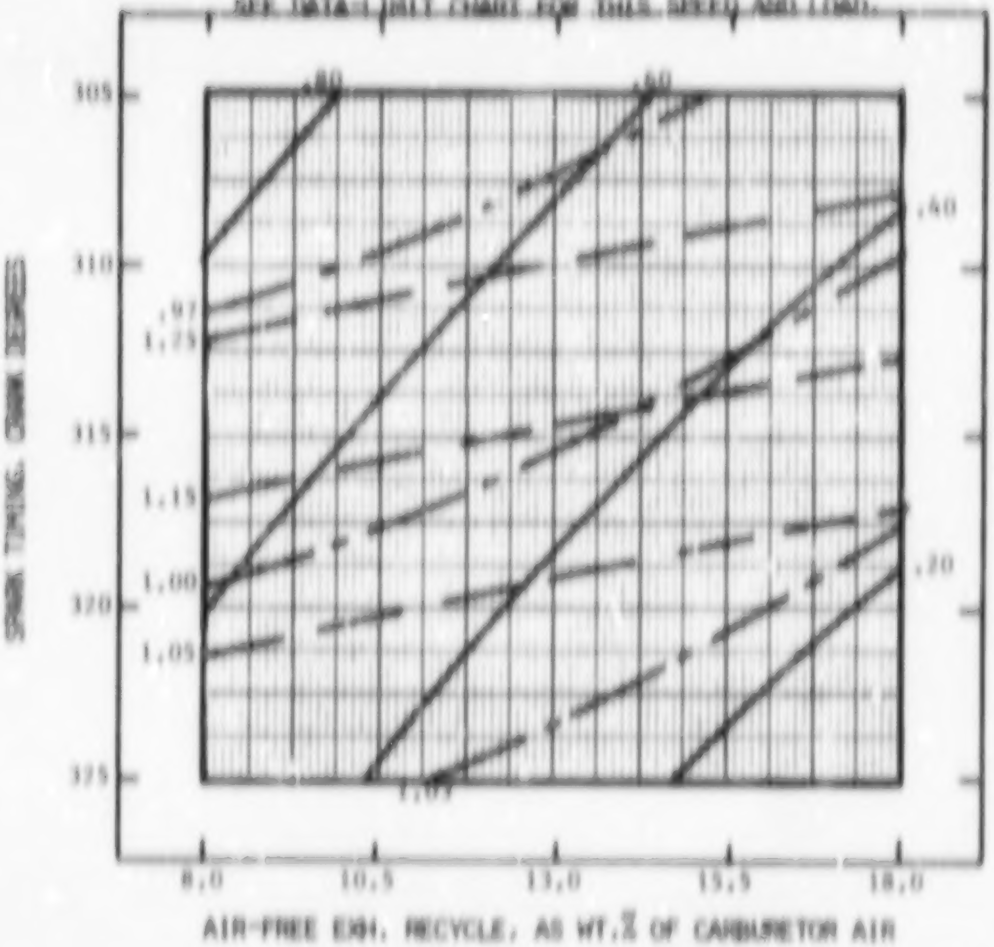
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-M A/F RATIO(2) 15.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.1418	3965 PPM NO	98.8
REL. # C6/HR. (FID)	— — — —	0.3935	690 PPM C6	88.6
REL. # CO/HR. (Not Plotted)	········	0.6516	0.26 %	98.6
REL. # FUEL/BHPHR.	– — –	0.5388		73.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.31

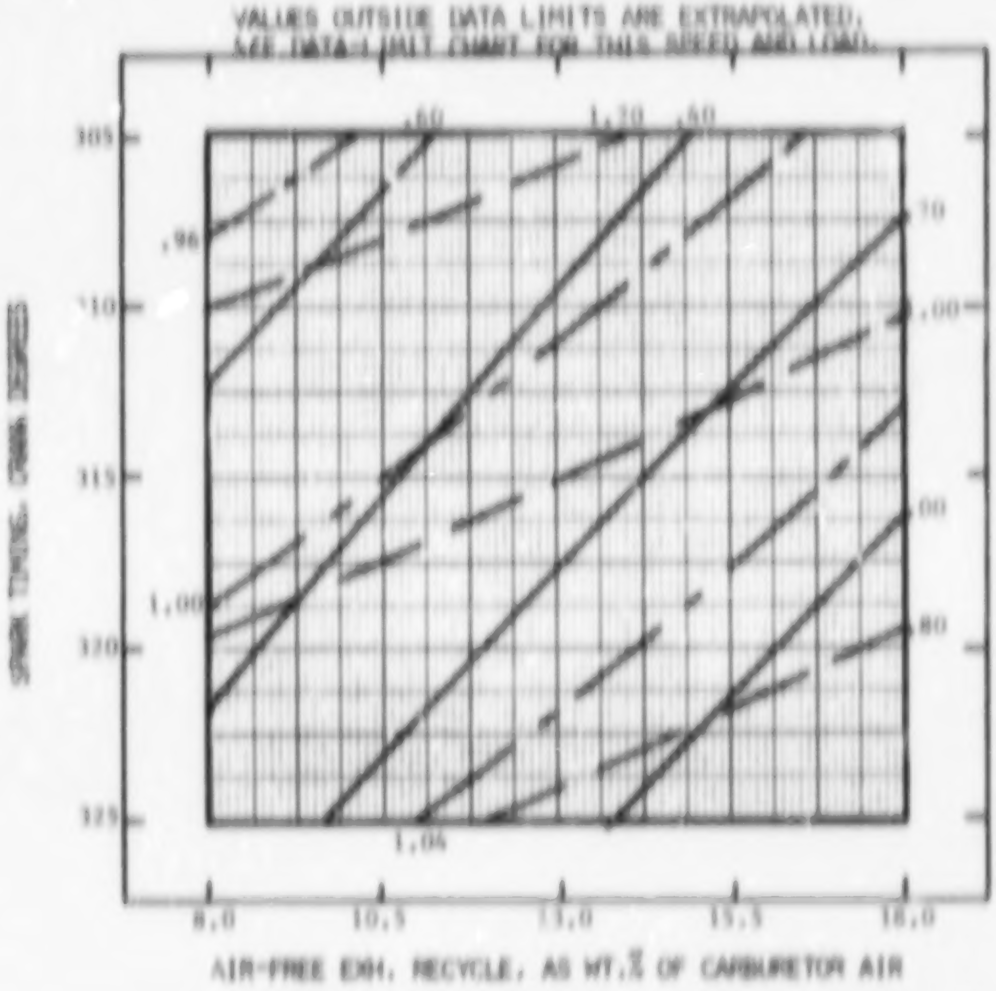
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	1000
CID	318	LB.-FT. TORQUE(1)	100
CONTROL SYSTEM	E+H	A/F RATIO(2)	16.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.7618	2061 PPM NO	59.8
REL. # C6HC/HR. (FID)	– – – –	0.3937	490 PPM C6	88.5
REL. # CO/HR. (Not Plotted)	-------	0.6516	0.26 %	98.6
REL. # FUEL/BHPHR.	– — –	0.3388		73.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MPR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.32

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

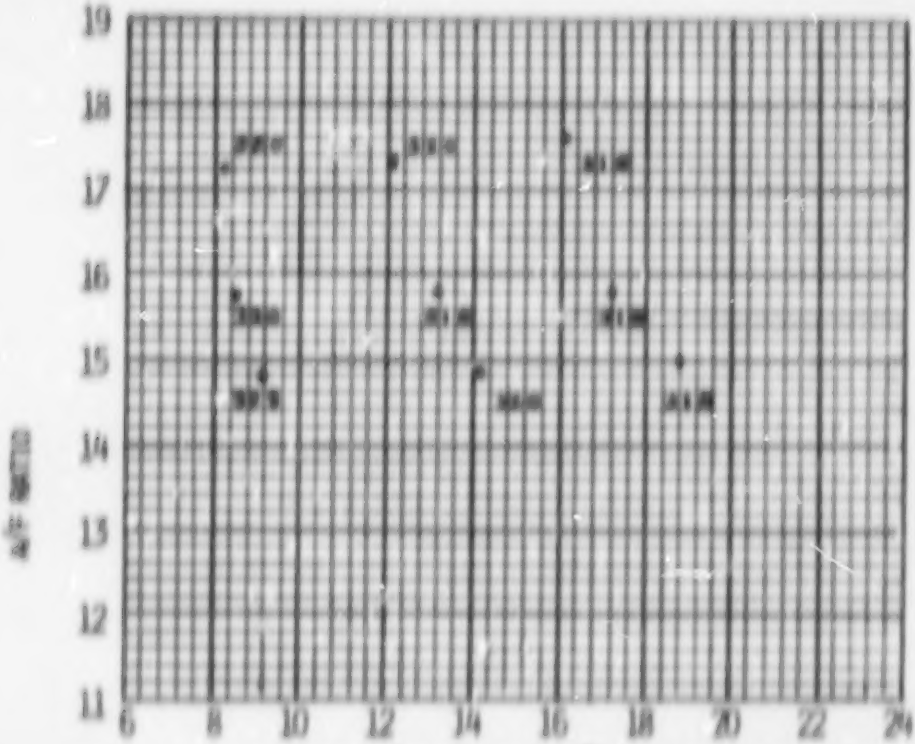
ENGINE: Plymouth RPM: 2000 LB.-FT. TQ. 150

MFR'S A/F: 13.6/1 MFR'S. SPARK: 337 IMAP(1) 19.7-19.8"HG.

CARB. AIR RATE(1) 6.61 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 16.4 = 16.6

Spk. 337 = 360

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.33

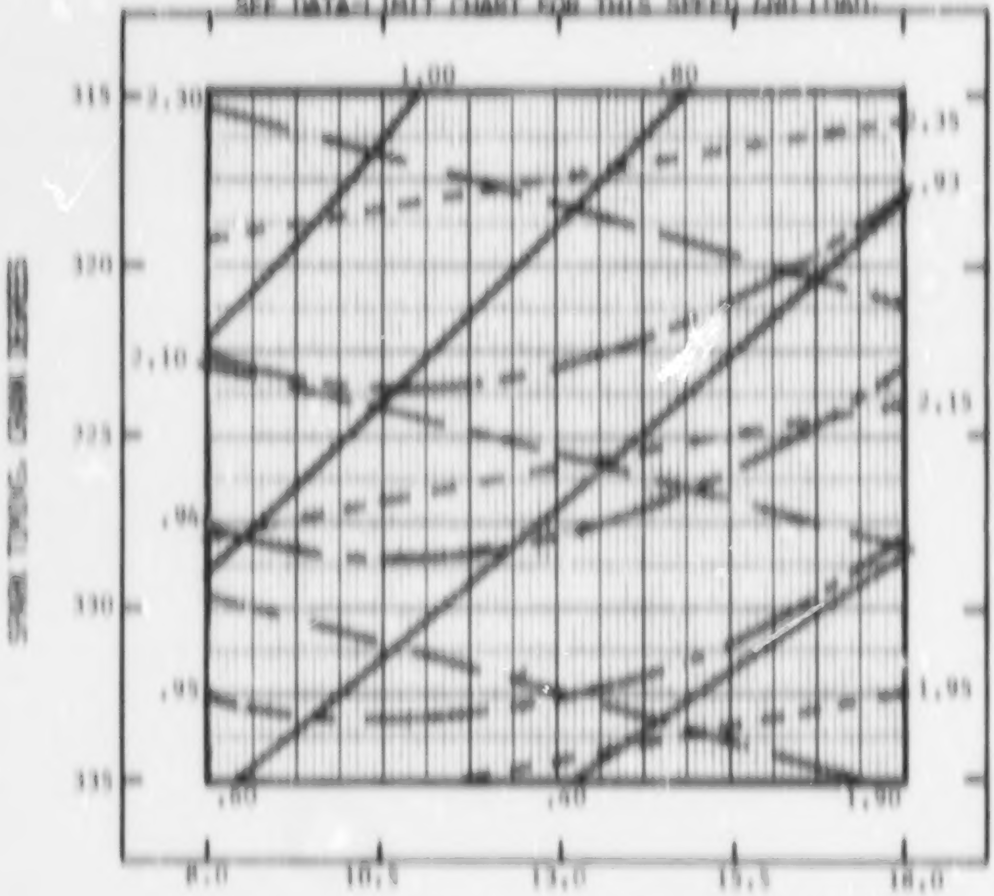
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 150
CONTROL SYSTEM E-R A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.7092	3030 PPM NO	96.9
REL. # C6HC/HR. (FID)	– – – –	0.3857	377 PPM C6	96.0
REL. # CO/HR.	‐‐‐‐‐‐‐	1.3180	0.38 %	88.0
REL. # FUEL/BHPHR.	– — –	0.6915		90.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

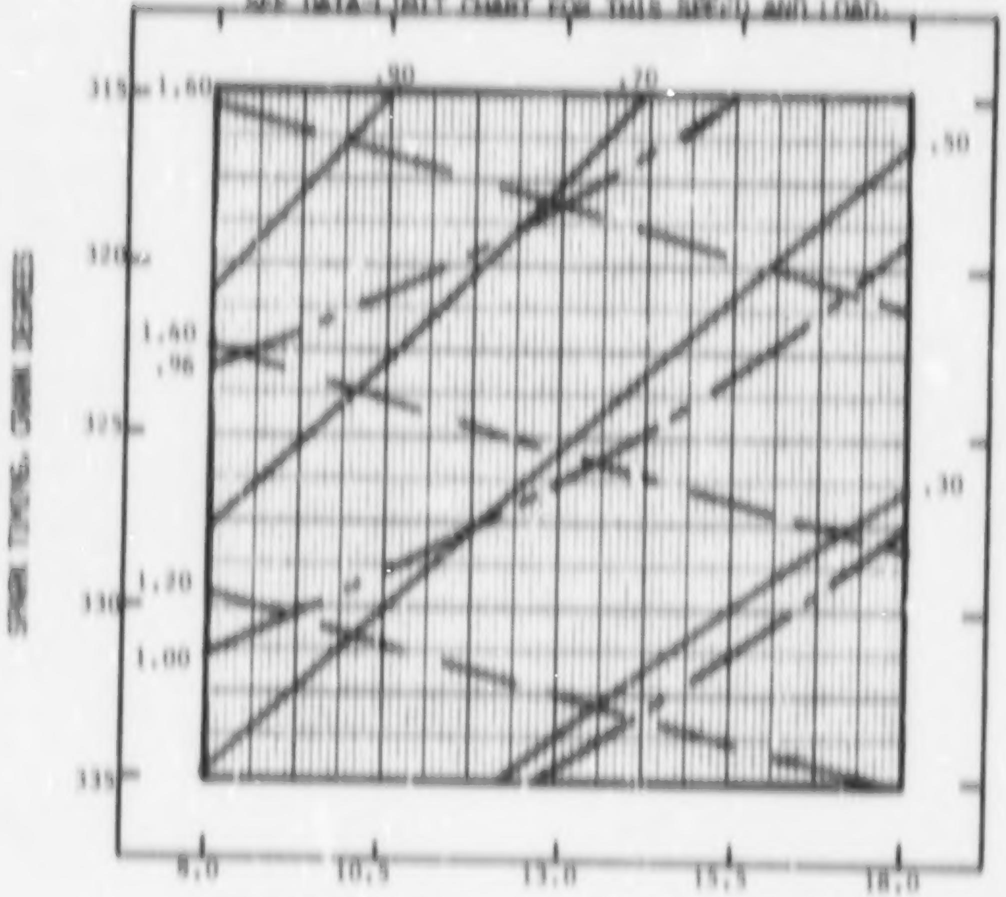
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MPR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.3A
USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000
CID 318 LB.-FT. TORQUE(1) 160
CONTROL SYSTEM E-M A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.7092	3030 PPM NO	96.9
REL. # C6HC/HR. (FID)	— — — —	0.3857	377 PPM C6	96.0
REL. # CO/HR. (Not Plotted)	-------	1.3180	0.38 %	88.0
REL. # FUEL/BHPHR.	— —— —	0.4915		90.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A2.35

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

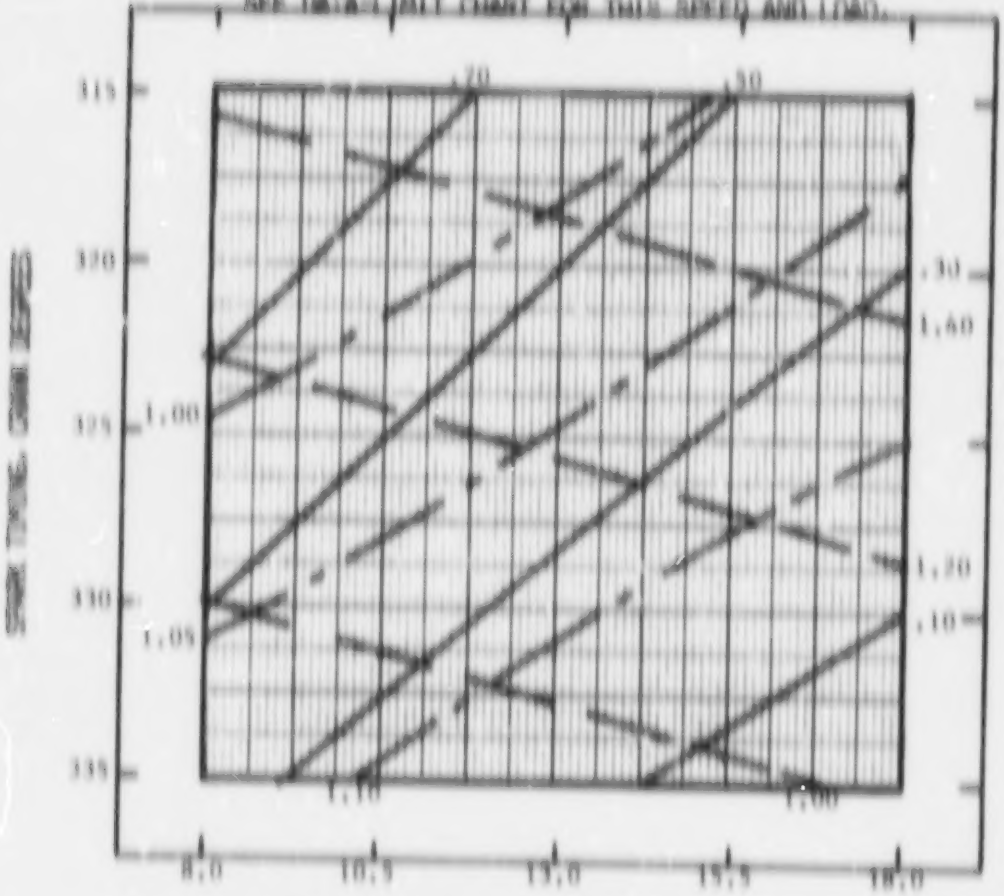
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2000

CID 318 LB.-FT. TORQUE(1) 140

CONTROL SYSTEM E-R A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.7092	3030 PPM NO	96.9
REL. # C6HC/HR. (FID)	– – – –	0.3857	377 PPM C6	96.0
REL. # CO/HR. (Not Plotted)	--------	1.3180	0.38 %	88.0
REL. # FUEL/BHPHR.	– — –	0.4915		90.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.36

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

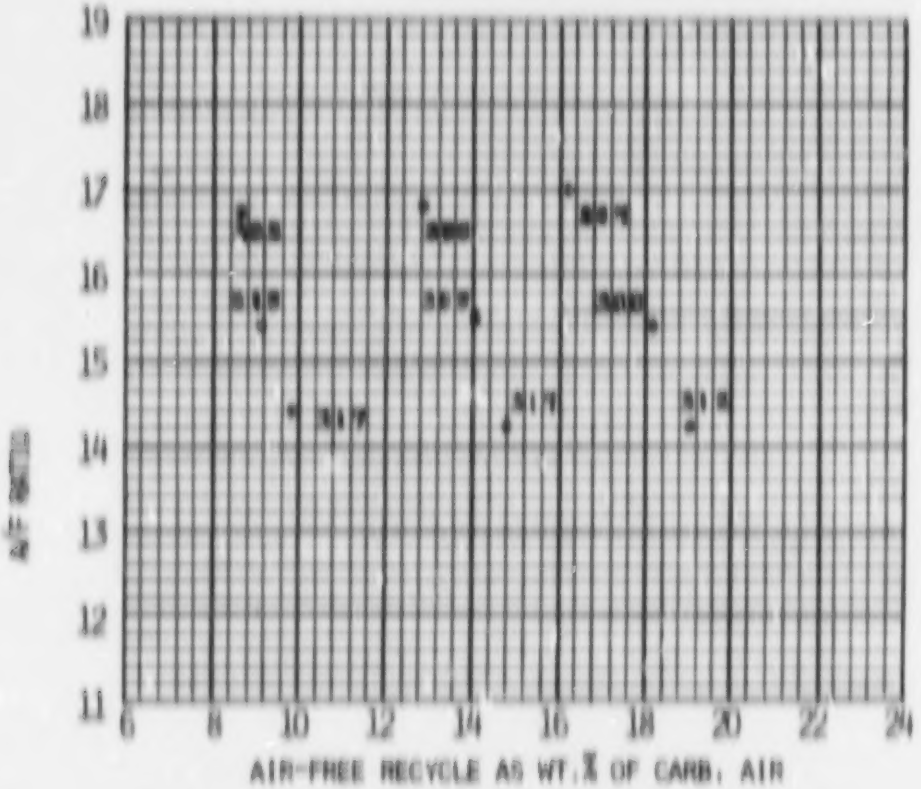
ENGINE: Plymouth RPM: 2500 LB.-FT. TQ. 50

MFR'S A/F: 15.6/1 MFR'S. SPARK: 317 IMAP(1) 11.5 "HG.

CARB. AIR RATE(1) 6.33 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 13.9 - 16.5
Spk. 317

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.37

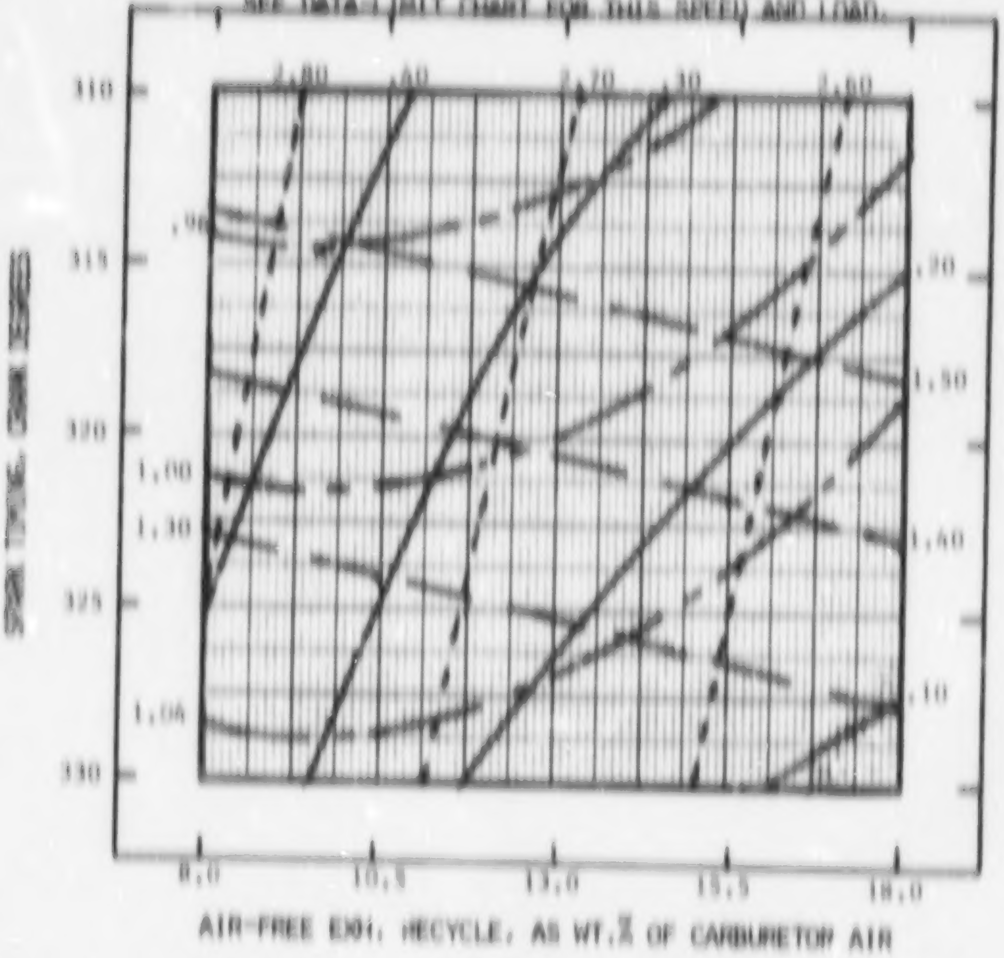
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2300
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.2322	3335 PPM NO	96.3
REL. # C6HC/HR. (FID)	– – – –	0.6050	602 PPM C6	89.6
REL. # CO/HR.	‒‒‒ ‐ ‒‒	0.8595	0.38 %	97.7
REL. # FUEL/BHPHR.	‐ ‒‒ ‐	0.7259		95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

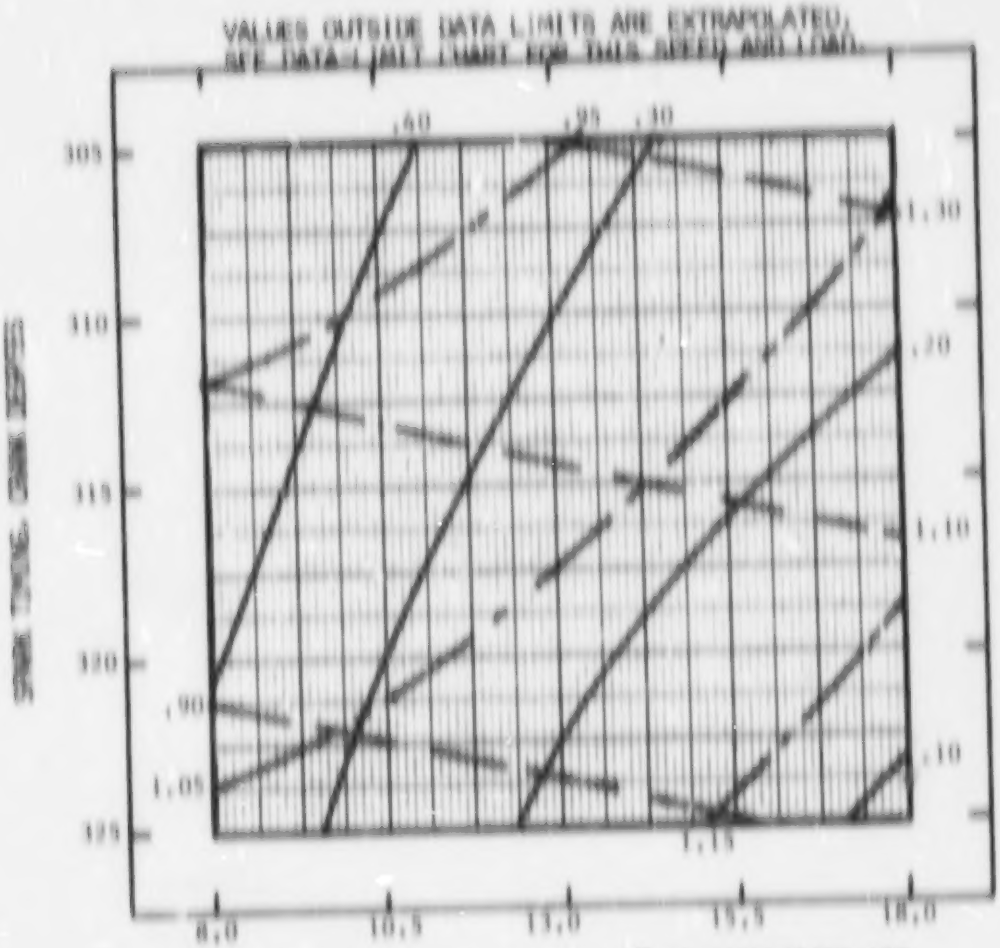
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.38

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2500
CID	318	LB.-FT. TORQUE(1)	50
CONTROL SYSTEM	E-4	A/F RATIO(2)	15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.2322	1335 PPM NO	96.3
REL. # C6HC/HR. (FID)	– – – –	0.6050	602 PPM C6	89.6
REL. # CO/HR. (Not Plotted)	········	0.8595	0.38 %	97.7
REL. # FUEL/BHPHR.	– — –	0.7259		95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

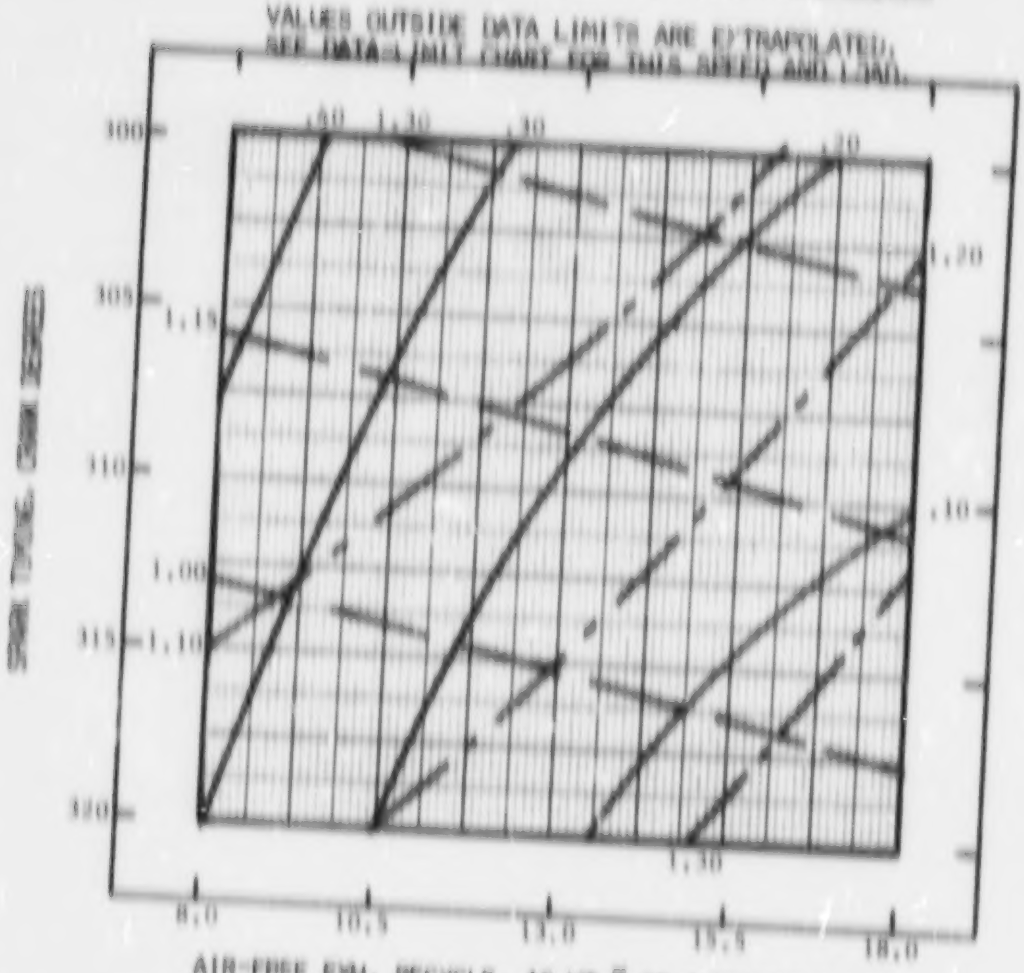
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.39
USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth
ENGINE RPM 2500
CID 318
LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-H
A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.2322	3335 PPM NO	96.3
REL. # C6HC/HR. (FID)	— — —	0.4050	607 PPM C6	89.6
REL. # CO/HR. (Not Plotted)	·······	0.8595	0.38 %	97.7
REL. # FUEL/BHPHR.	— · —	0.7259		95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.40

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

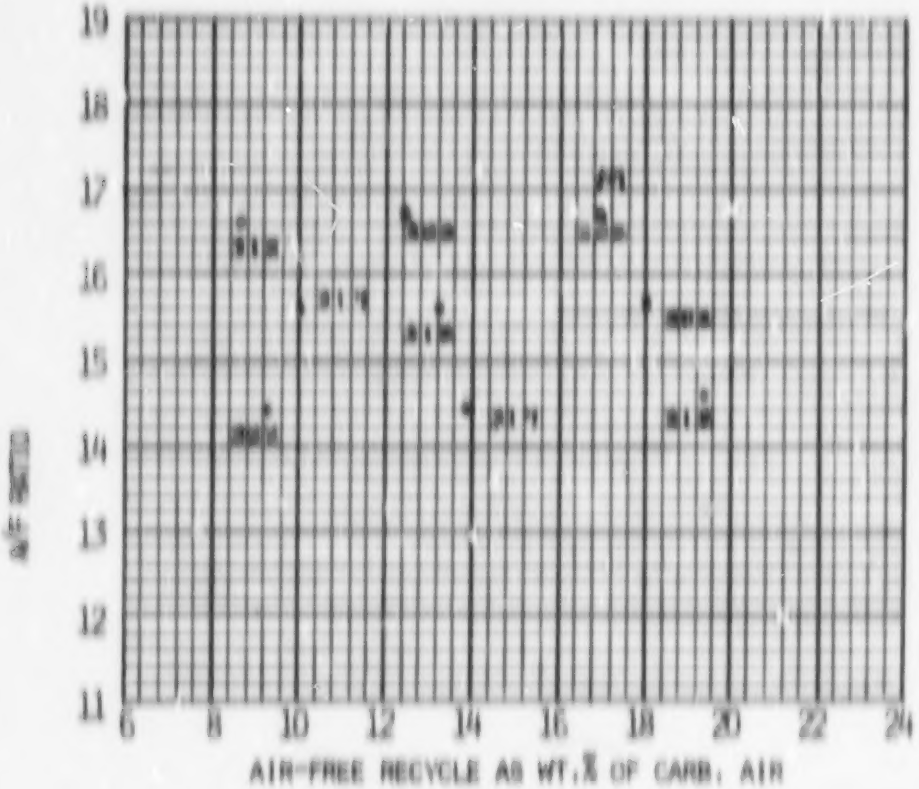
ENGINE: Plymouth RPM: 2500 LB.-FT. TQ. 75

MFR'S A/F: 15.4/1 MFR'S. SPARK: 317 IMAP(1) 13.8-14.2 "HG.

CARB. AIR RATE(1) 3.36 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle
A/F 14.4 = 16.4
Spk. 317

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A7.41

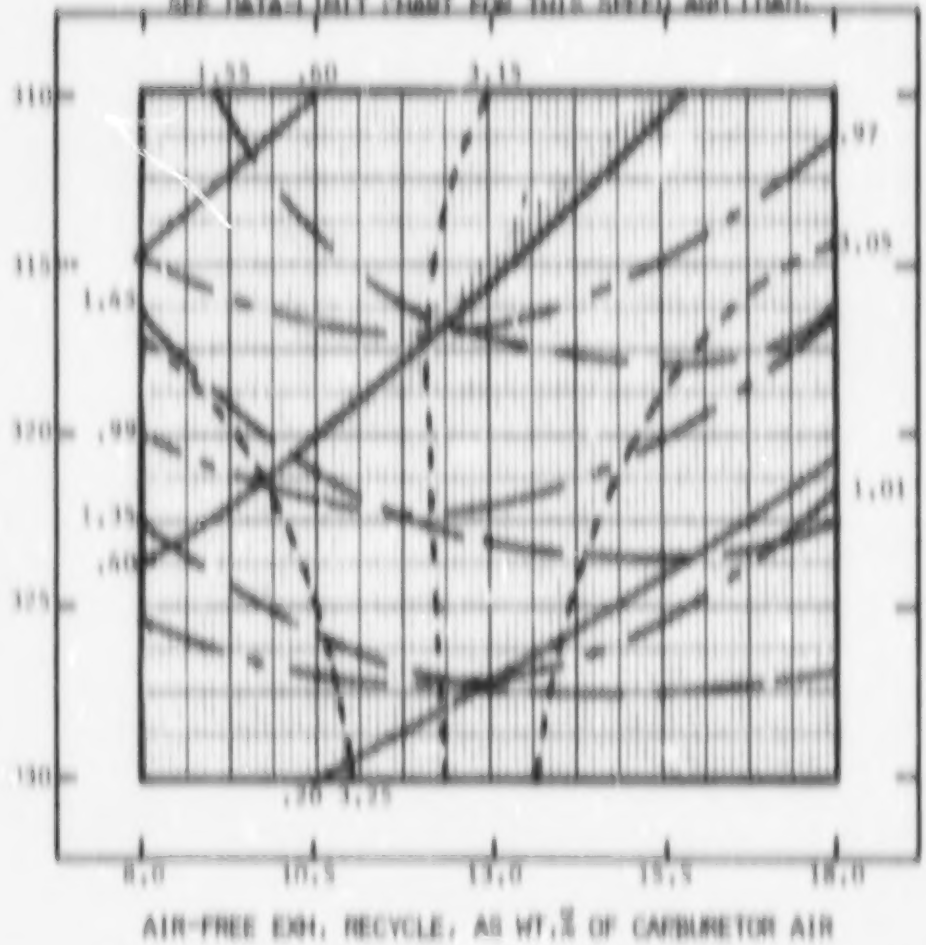
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2500
CID	318	LB.-FT. TORQUE(1)	75
CONTROL SYSTEM	E-H	A/F RATIO(2)	14.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	2.0026	8256 PPM NO	99.2
REL. # C_6HC/HR. (FID)	– – – –	0.5387	628 PPM C_6	87.0
REL. # CO/HR.	------	1.0528	0.37 %	99.0
REL. # FUEL/BHPHR.	– — –	0.6095		86.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK. NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.42

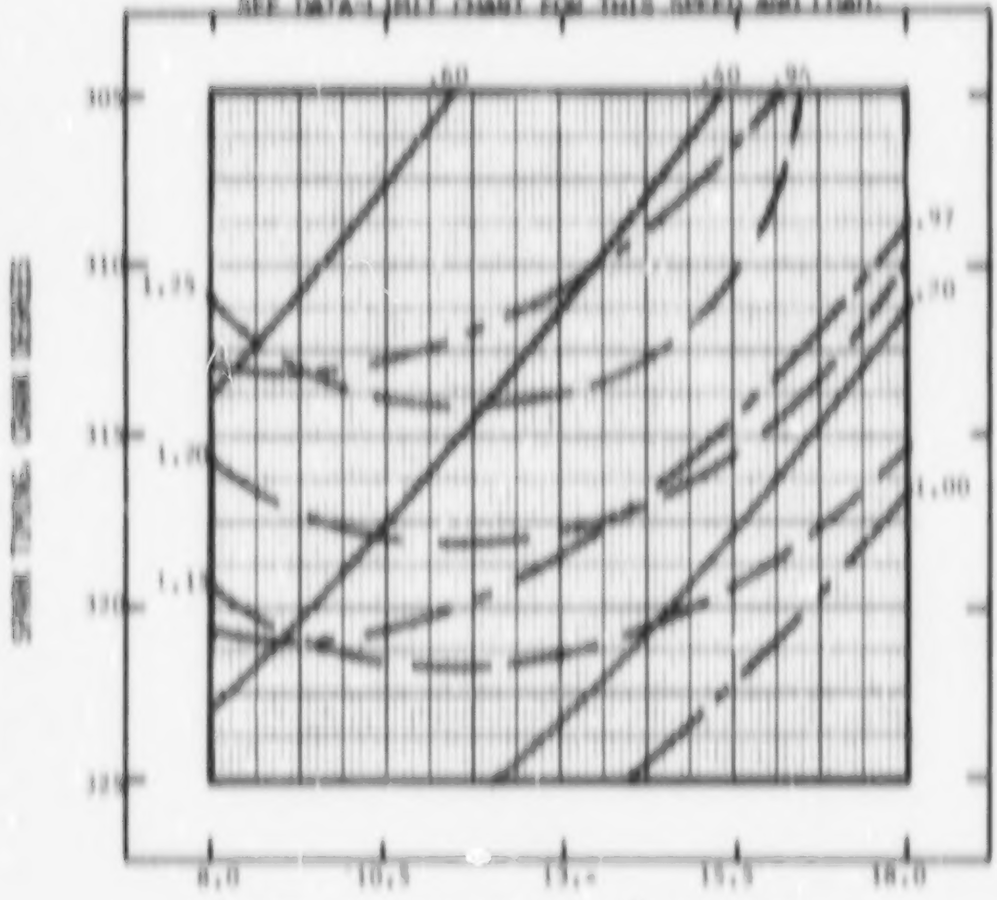
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2500
CID 318 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM E-H A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	2.0026	4254	PPM NO	99.2
REL. # C6/HC/HR. (FID)	– – – –	0.5387	678	PPM C6	87.0
REL. # CO/HR. (Not Plotted)	--------	1.0528	0.37	%	99.0
REL. # FUEL/BHPHR.	— — —	0.6095			86.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.43

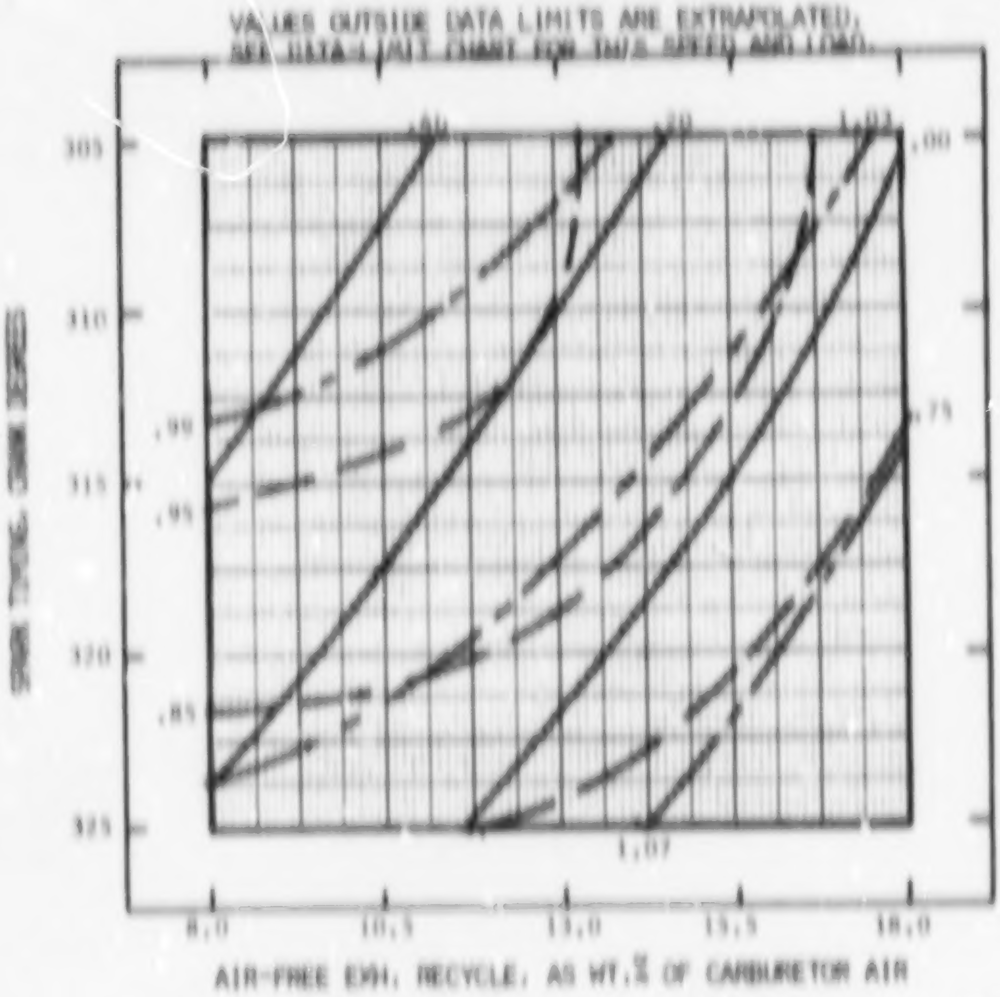
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2500
CID 318 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	2.0076	6255 PPM NO	99.2
REL. # C6HC/HR. (FID)	– – – –	0.5382	628 PPM C6	87.0
REL. # CO/HR. (Not Plotted)	--------	1.0528	0.32 %	99.0
REL. # FUEL/BHPHR.	— - — -	0.6095		86.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.55

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

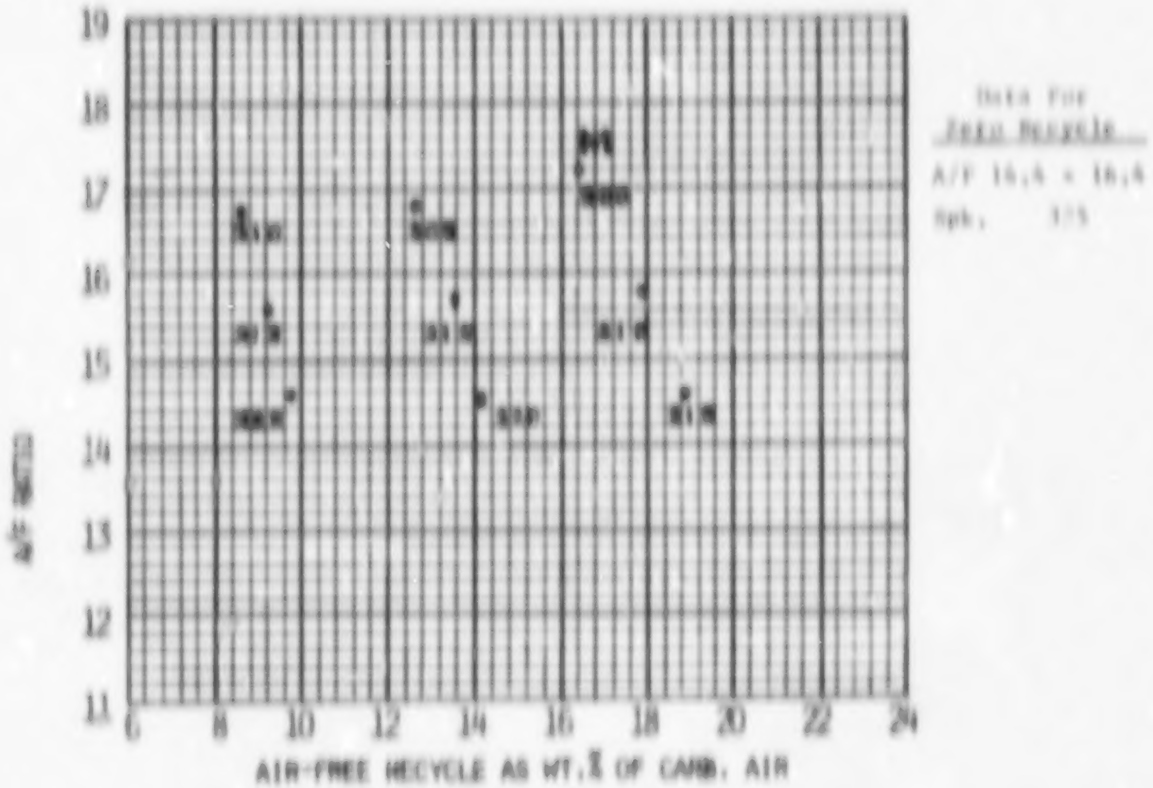
ENGINE: Plymouth RPM: 2500 LB.-FT. TQ. 100

MFR'S A/F: 13.4/1 MFR'S. SPARK: 325 IMAP(1) 16.1-16.5 "HG.

CARB. AIR RATE(1) 6.64 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.43

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

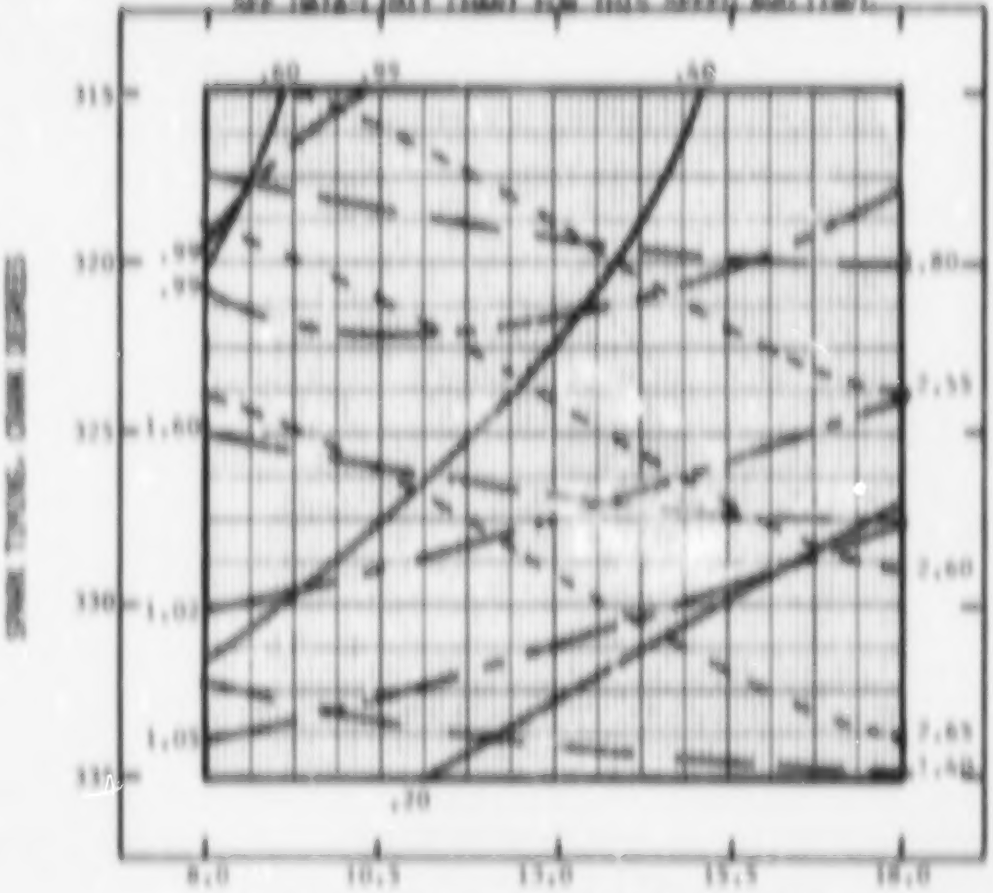
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2500

CID 318 LB.-FT. TORQUE(1) 100

CONTROL SYSTEM E-H A/F RATIO(2) 15.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.1536	1061 PPM NO	97.2
REL. # C6H14/HR. (FID)	- - - -	0.6765	557 PPM C6	98.1
REL. # CO/HR.	--------	1.6928	0.55 %	98.1
REL. # FUEL/BHPHR.	— — —	0.5660		87.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.47

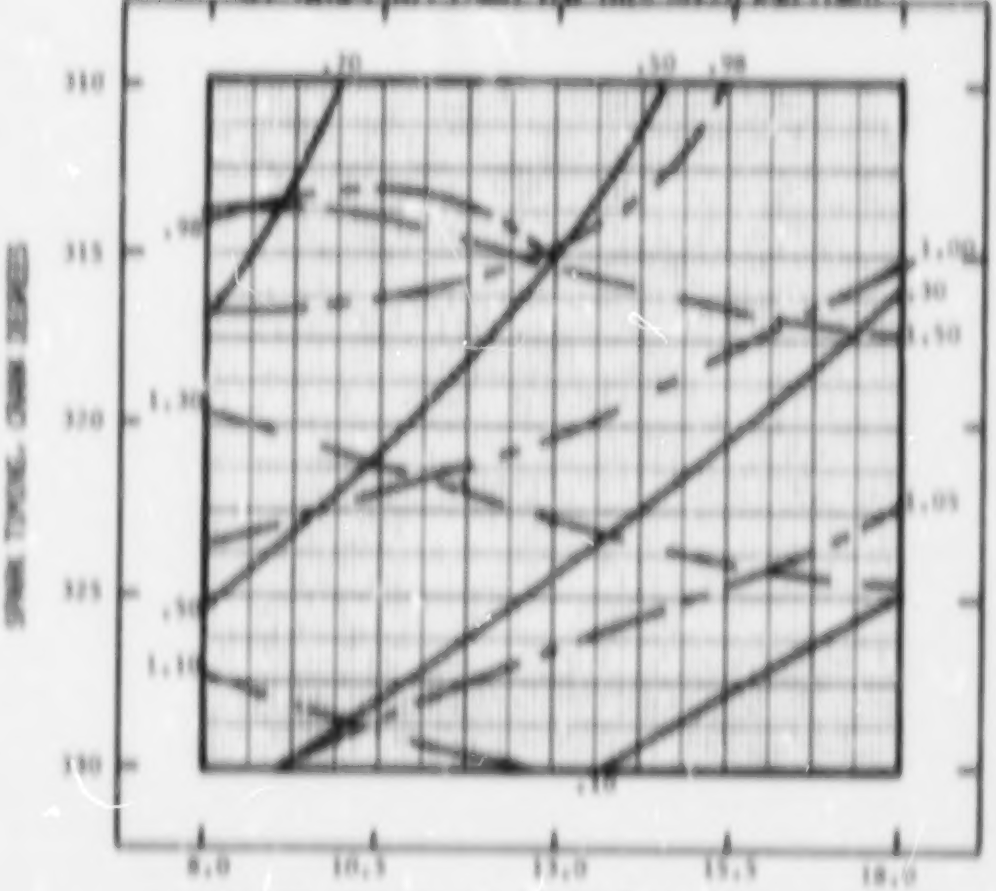
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2300
CID	318	LB.-FT. TORQUE(1)	100
CONTROL SYSTEM	E-M	A/F RATIO(2)	15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.1630	3063 PPM NO	97.2
REL. # C6H14/HR. (FID)	– – – –	0.5215	467 PPM C6	98.1
REL. # CO/HR. (Not Plotted)	-------	1.0268	0.66 %	98.2
REL. # FUEL/BHPHR.	– — –	0.5420		87.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL.: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.47

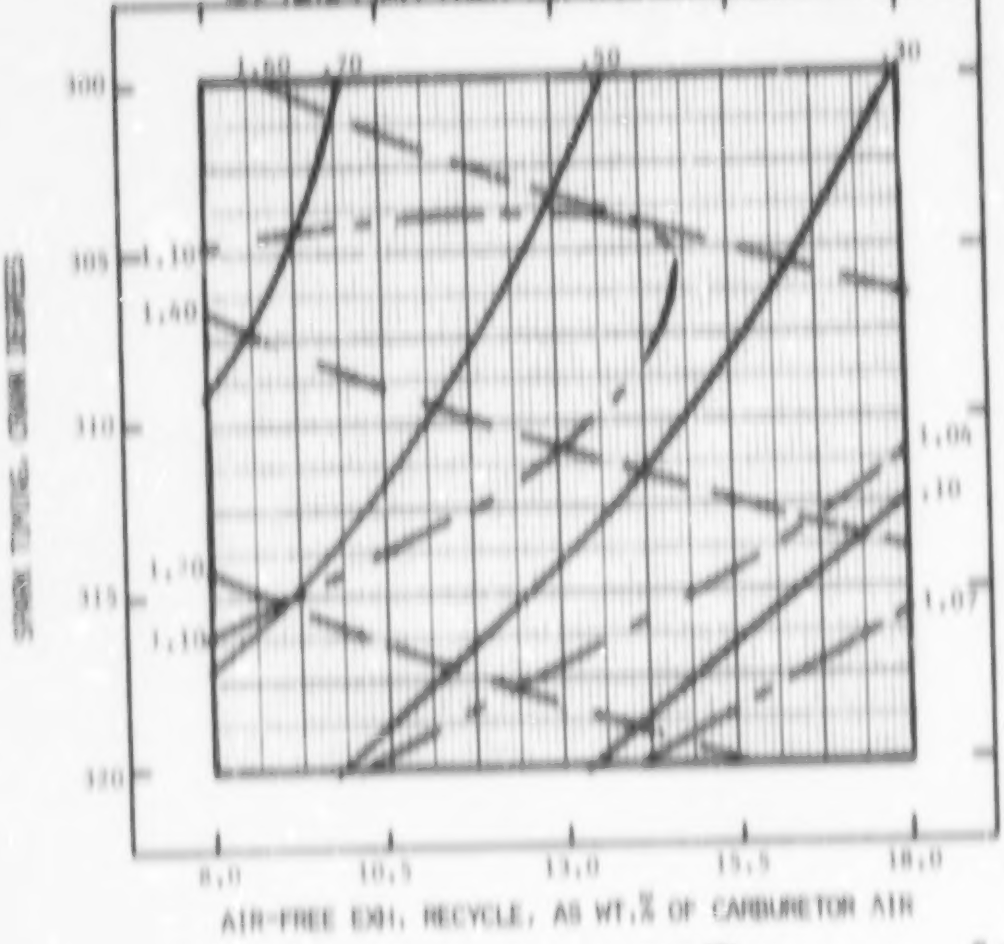
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2500
CID	318	LB.-FT. TORQUE(1)	100
CONTROL SYSTEM	E-H	A/F RATIO(2)	16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.1656	3863 PPM NO	99.2
REL. # C$_6$/C/HR. (FID)	– – – –	0.6766	467 PPM C$_6$	98.1
REL. # CO/HR. (Not Plotted)	-------	1.6928	0.66 %	98.3
REL. # FUEL/BHPHR.	– — –	0.5660		89.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.48

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

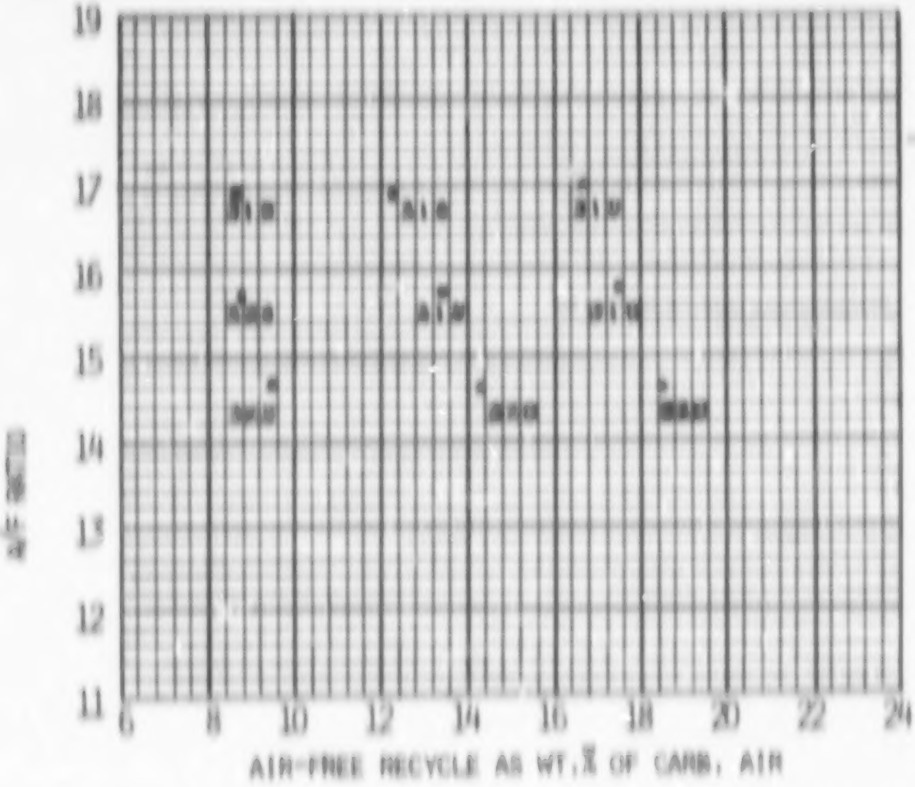
ENGINE: Plymouth RPM: 2500 LB.-FT. TQ. 140

MFR'S A/F: 15.4/1 MFR'S. SPARK: 33° IMAP(1) 20.2-20.5 "HG.

CARB. AIR RATE(1) 8.66 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle
A/F 14.6 - 16.6
Spk: 33°

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.49

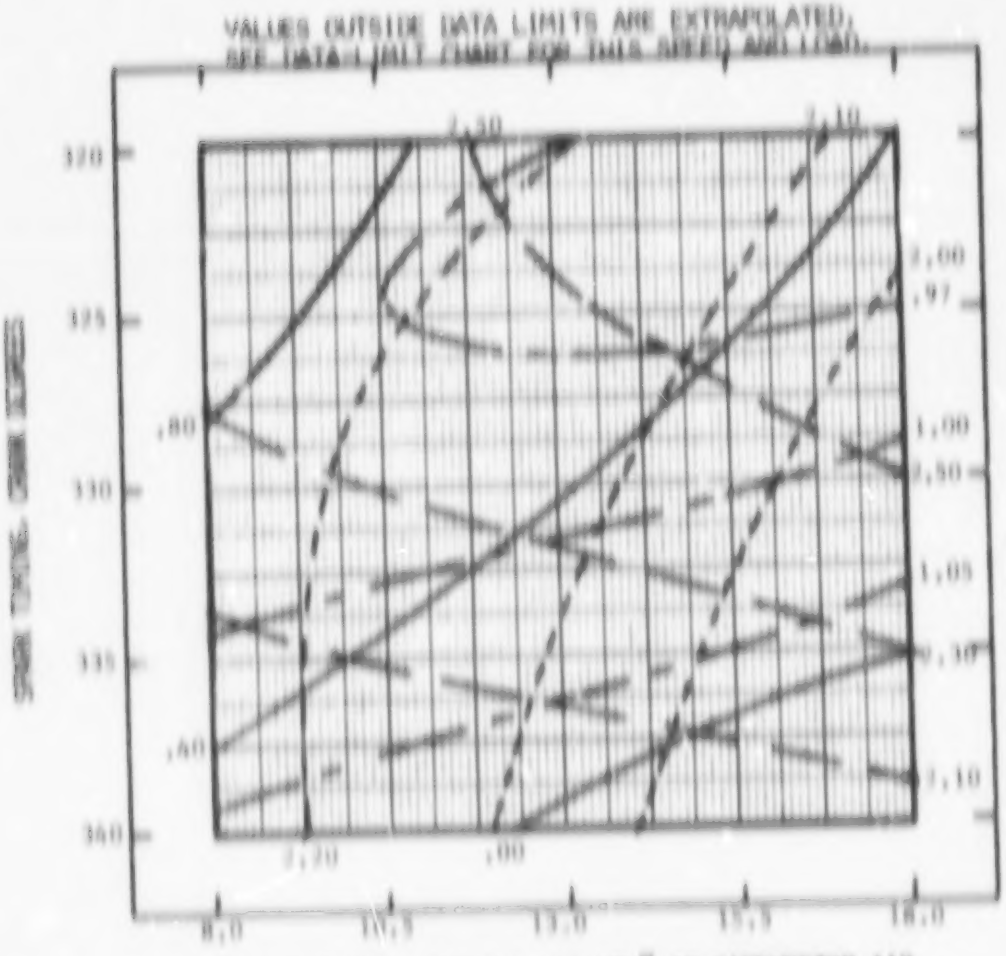
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2500
CID 318 LB.-FT. TORQUE(1) 160
CONTROL SYSTEM E-H A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	2.1386	2960 PPM NO	96.2
REL. # C6H14/HR. (FID)	— — — —	0.1960	297 PPM C6	98.5
REL. # CO/HR.	- - - - - - -	1.9557	0.55 %	98.3
REL. # FUEL/BHPHR.	— — —	0.3055		96.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.30

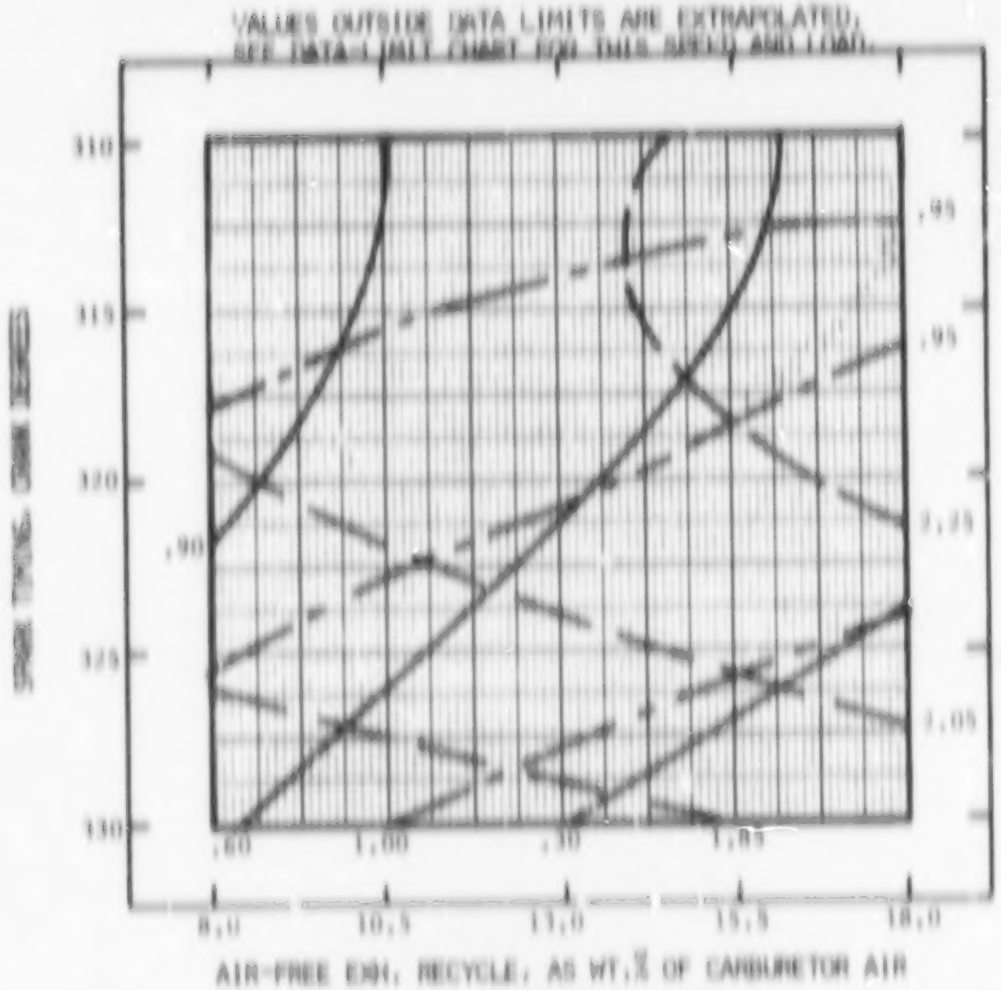
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Plymouth	ENGINE RPM	2500
CID	318	LB.-FT. TORQUE(1)	150
CONTROL SYSTEM	E-H	A/F RATIO(2)	15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	2.1380	2960 PPM NO	96.2
REL. # C6HC/HR. (FID)	- - - -	0.3960	297 PPM C6	98.5
REL. # CO/HR. (Not Plotted)	·······	1.9562	0.66 %	98.2
REL. # FUEL/BHPHR.	- — -	0.5055		96.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Homograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.51

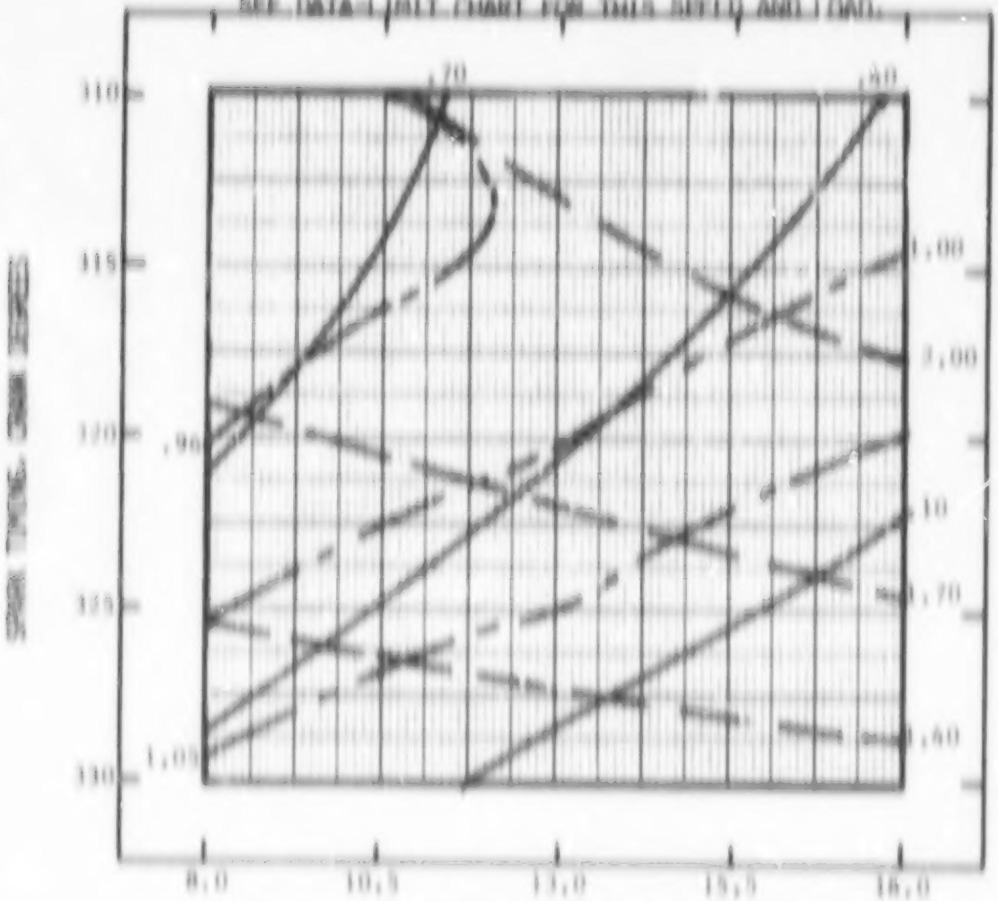
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 2500
CID 318 LB.-FT. TORQUE(1) 160
CONTROL SYSTEM ExR A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	2.1386	1960 PPM NO	96.2
REL. # C6/HC/HR. (FID)	- - - -	0.3960	397 PPM C6	98.4
REL. # CO/HR. (Not Plotted)	······	1.9547	0.55 %	98.7
REL. # FUEL/BHPHR.	— — —	0.5055		96.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A2.57

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

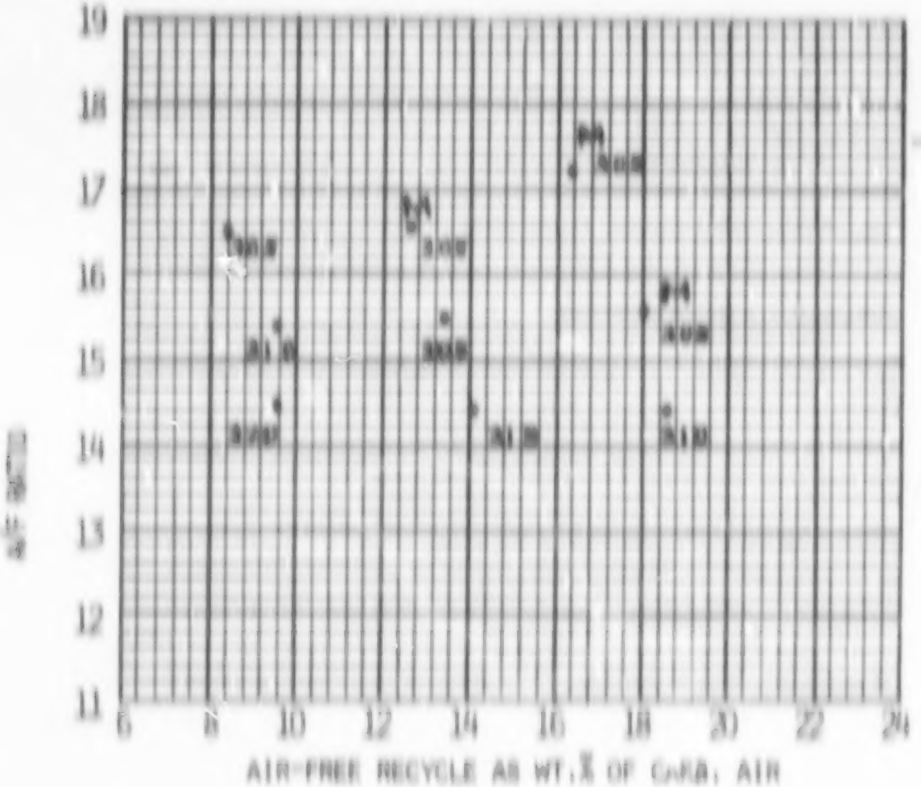
ENGINE: Plymouth RPM: 3000 LB.-FT. TQ. 50

MFR'S A/F: 13.5/1 MFR'S. SPARK: 11B IMAP(1) 11.8 "HG.

CARB. AIR RATE(1) 3.44 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data For
Zero Recycle

A/F 14.6 = 14.6
Spk. 11B

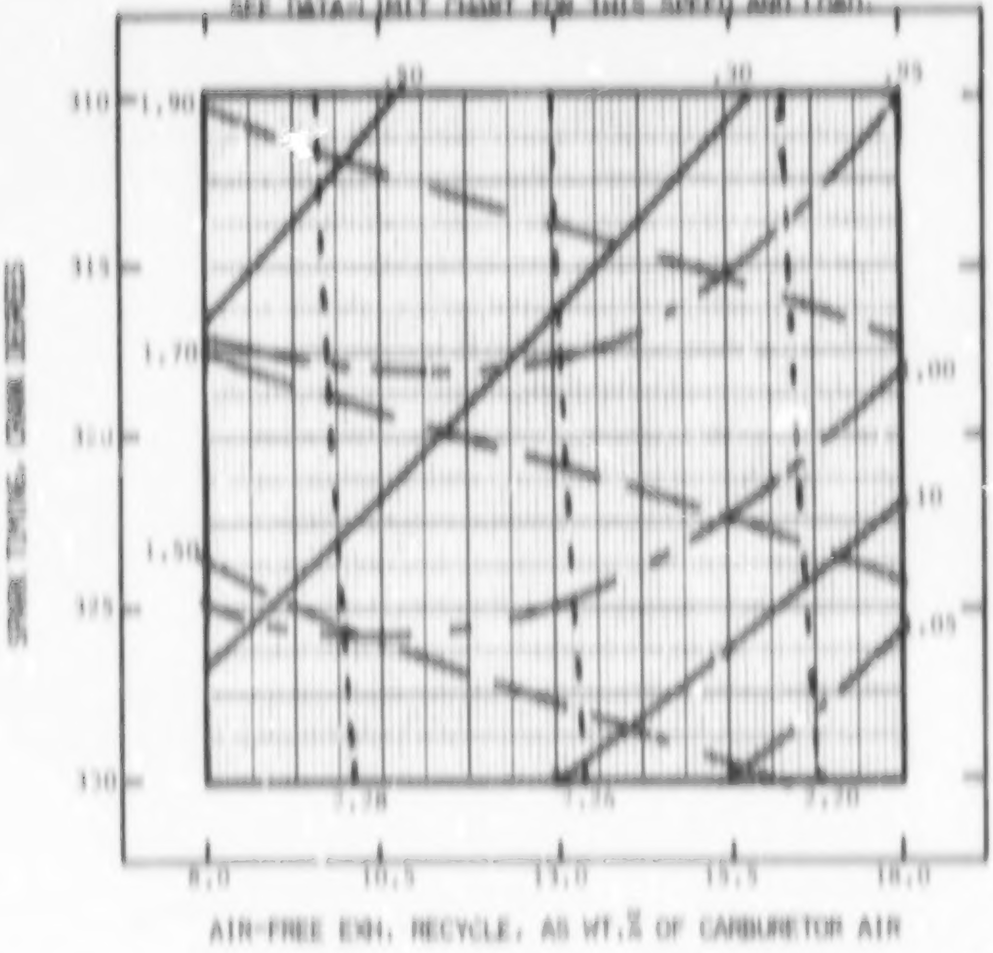
(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.51
USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth
ENGINE RPM 3000
CID 318
LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-H
A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.7281	1758 PPM NO	99.1
REL. # C6HC/HR. (FID)	- - - -	0.3718	.555 PPM C6	98.1
REL. # CO/HR.	-·-·-·	1.2773	0.56 %	79.2
REL. # FUEL/BHPHR.	— — —	0.7550		85.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.34

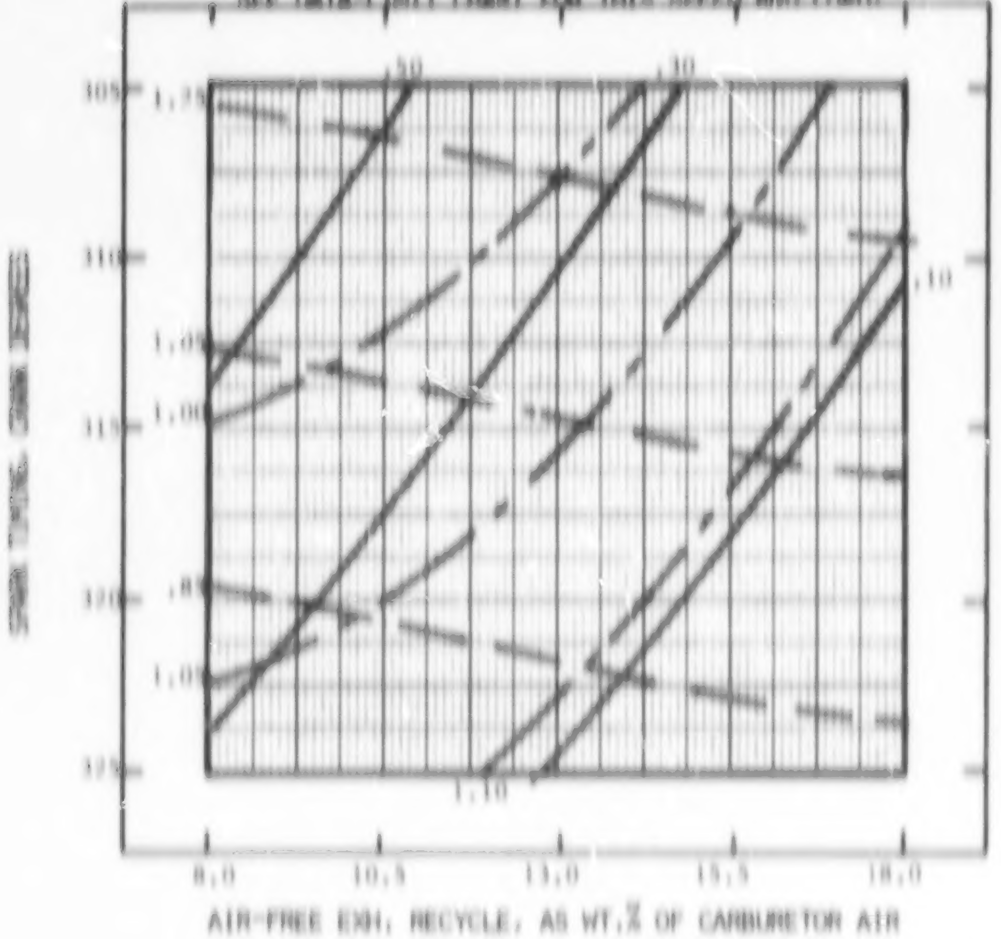
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 3000
CID 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-M A/F RATIO(2) 15.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.7281	3758 PPM NO	99.1
REL. # C6HC/HR. (FID)	- - - - -	0.3718	555 PPM C6	98.3
REL. # CO/HR. (Not Plotted)	-------	1.1773	0.66 %	99.2
REL. # FUEL/BHPHR.	— — —	0.7660		86.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

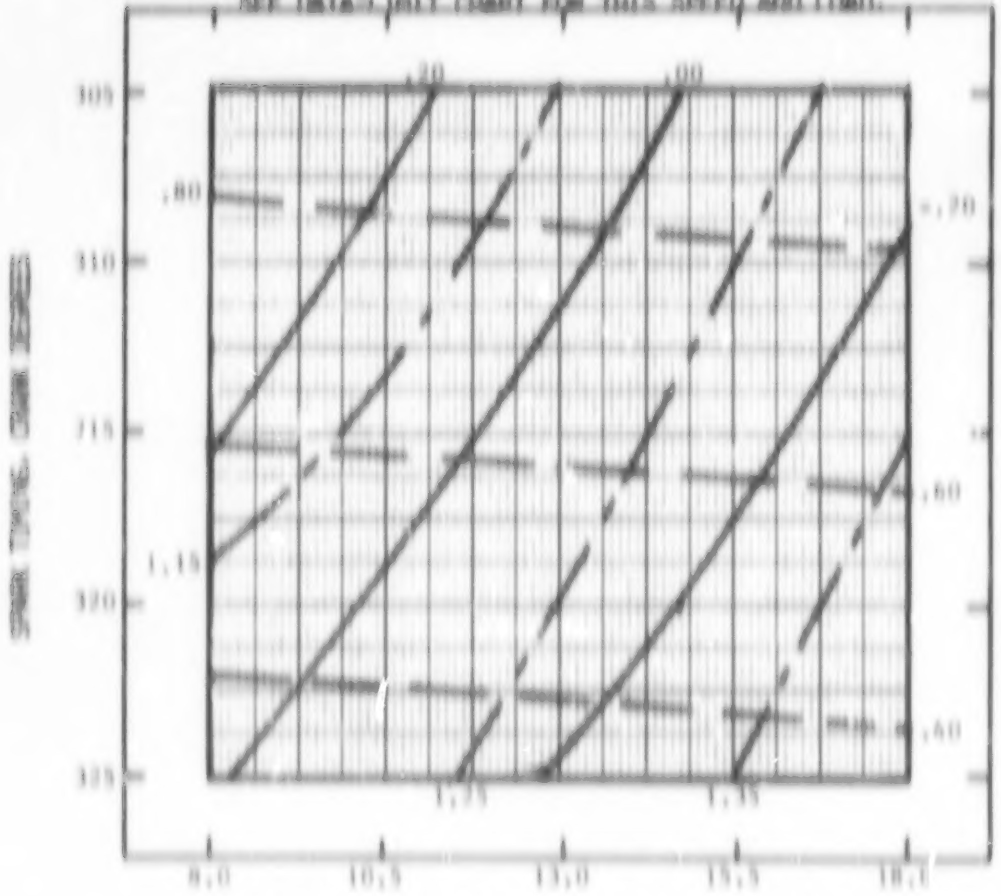
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.55
USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 3000
C.I.D 318 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM E-H A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.7281	3758 PPM NO	99.1
REL. # C6/HC/HR. (FID)	═ ═ ═ ═	0.3718	555 PPM C6	98.3
REL. # CO/HR. (Not Plotted)	········	1.2773	0.56 %	99.3
REL. # FUEL/BHPHR.	━ ━━ ━	0.7650		85.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.37

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

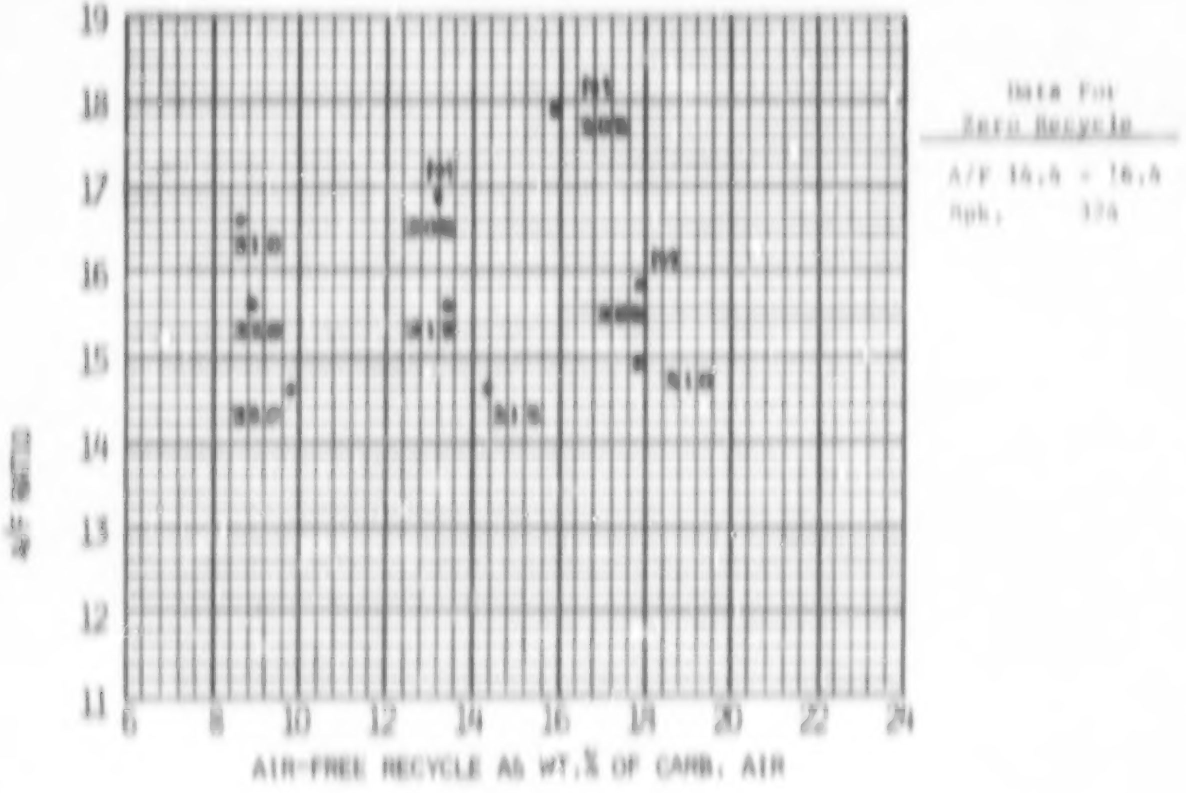
ENGINE: Plymouth RPM: 2000 LB.-FT. TQ. 100

MFR'S A/F: 13.6/1 MFR'S. SPARK: 12° IMAP(1) 16.6 "HG.

CARB. AIR RATE(1) 4.09 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



AIR-FREE RECYCLE AS WT.% OF CARB. AIR

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.37

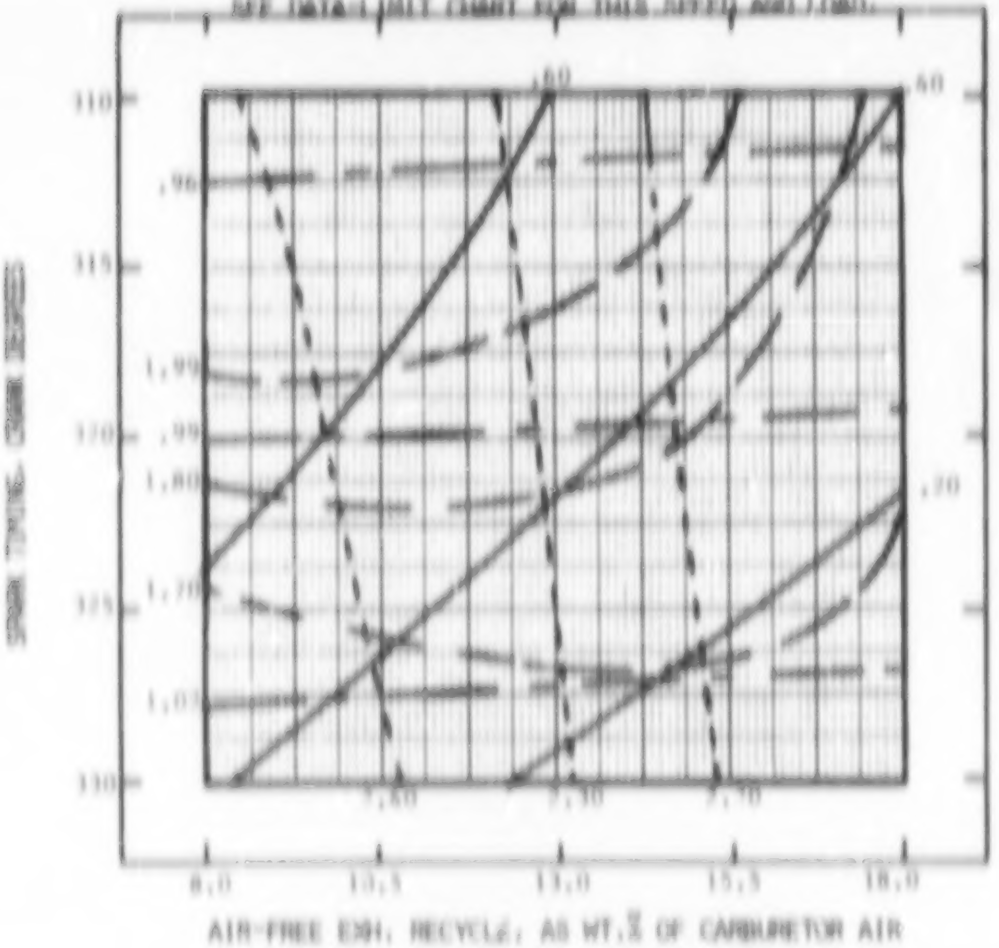
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 3000
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-M A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6165	3857 PPM NO	98.8
REL. # C6HC/HR. (FID)	– – – –	0.6851	120 PPM C6	96.2
REL. # CO/HR.	-------	1.8558	0.65 %	93.1
REL. # FUEL/BHPHR.	– — –	0.5530		76.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph
(3) MEAN VALUE AT MFR'S. A/F AND SPARK. NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.10

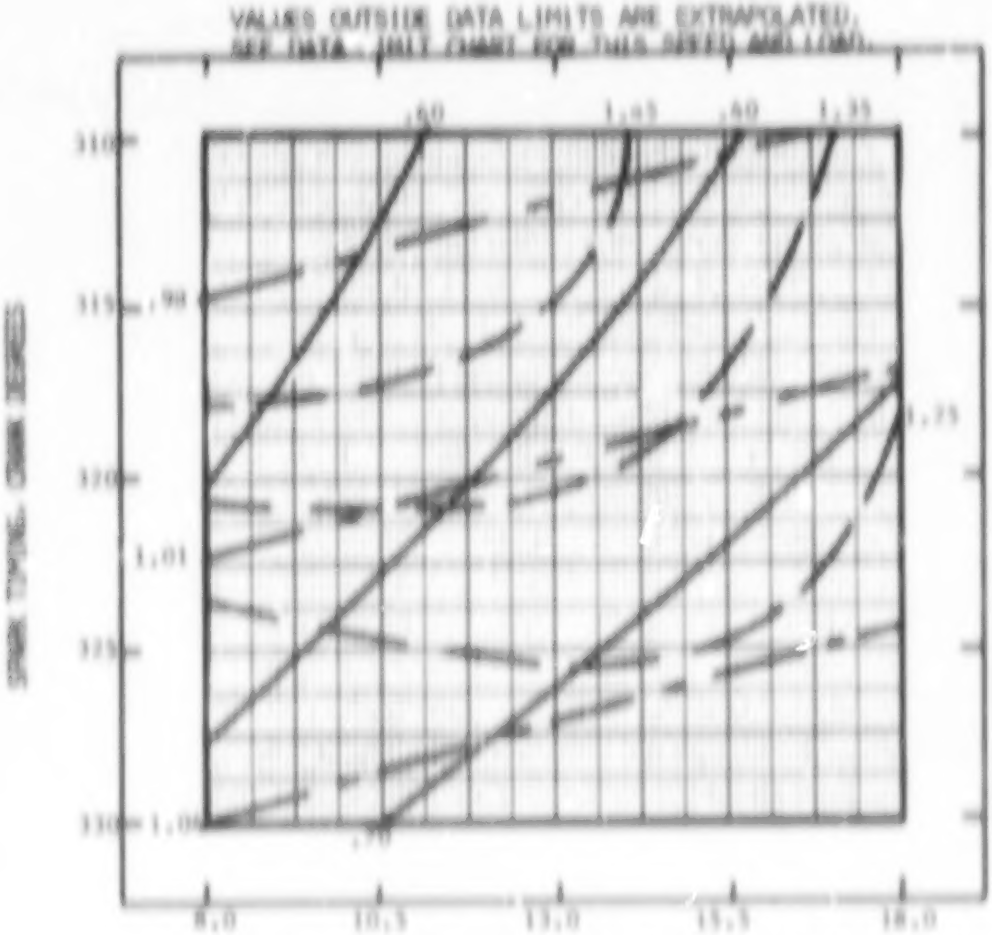
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth ENGINE RPM 3000
CID 318 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-H A/F RATIO(2) 15.1

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA - LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	1.6164	1857 PPM NO	98.8
REL. # C6HC/HR. (FID)	– – – –	0.5863	390 PPM C6	76.1
REL. # CO/HR. (Not Plotted)	--------	1.8558	0.65 %	93.1
REL. # FUEL/BHPHR.	– —— –	0.5570		78.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT RPM'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.39

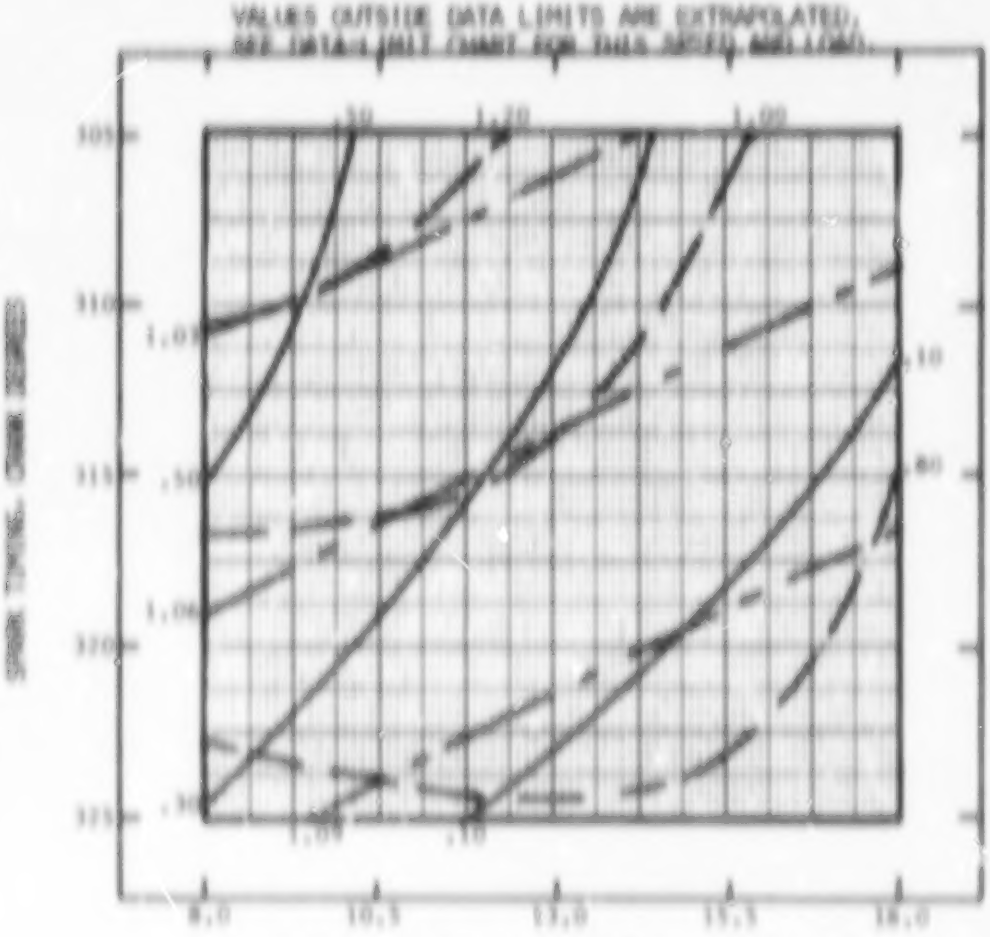
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Plymouth
ENGINE RPM 3000
CID 318
LB.-FT. TORQUE(1) 100
CONTROL SYSTEM E-R
A/F RATIO(2) 16.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS ENGINE AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	2.6166	3657 PPM NO	98.8
REL. # C6H14/HR. (FID)	— — — —	0.5863	390 PPM C6	96.2
REL. # CO/HR. (Not Plotted)	--------	1.8558	0.63 %	93.2
REL. # FUEL/BHPHR.	— —— —	0.5530		78.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Leonard Nomograph

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

DATA FOR VALIANT

FIGURE A2.60

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

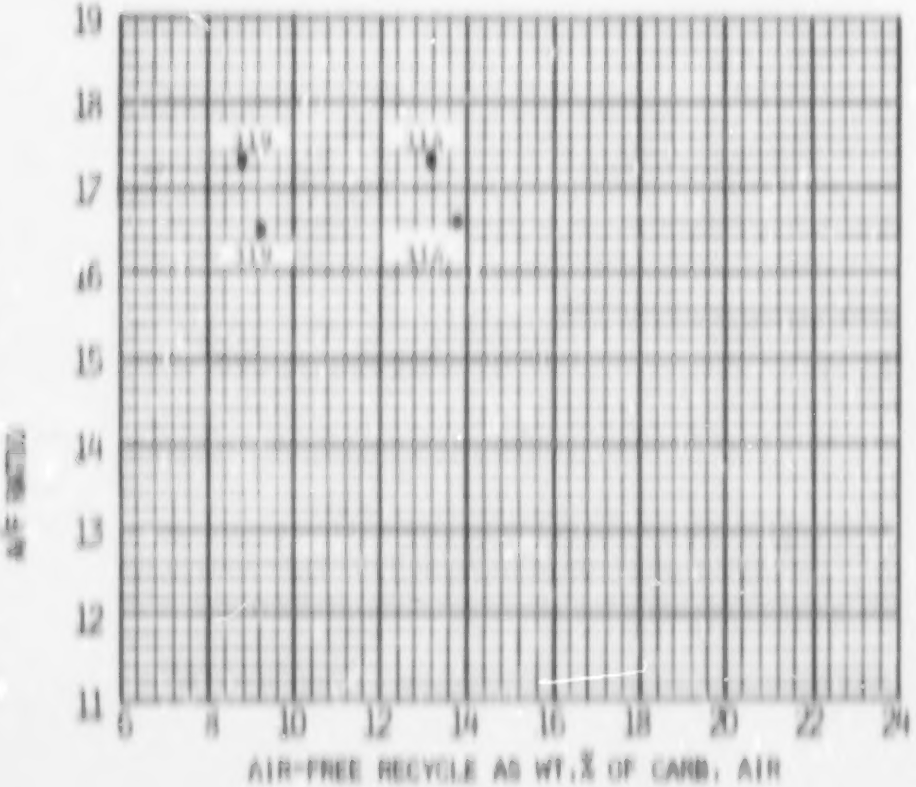
ENGINE: Valiant RPM: 1500 LB.-FT. TQ. 10

MFR'S A/F: 16.0 MFR'S. SPARK: 125 IMAP(1) 11.8 "HG.

CARB. AIR RATE(1) 1.60 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 15.1-16.6
Spk. 126-129

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A7.61

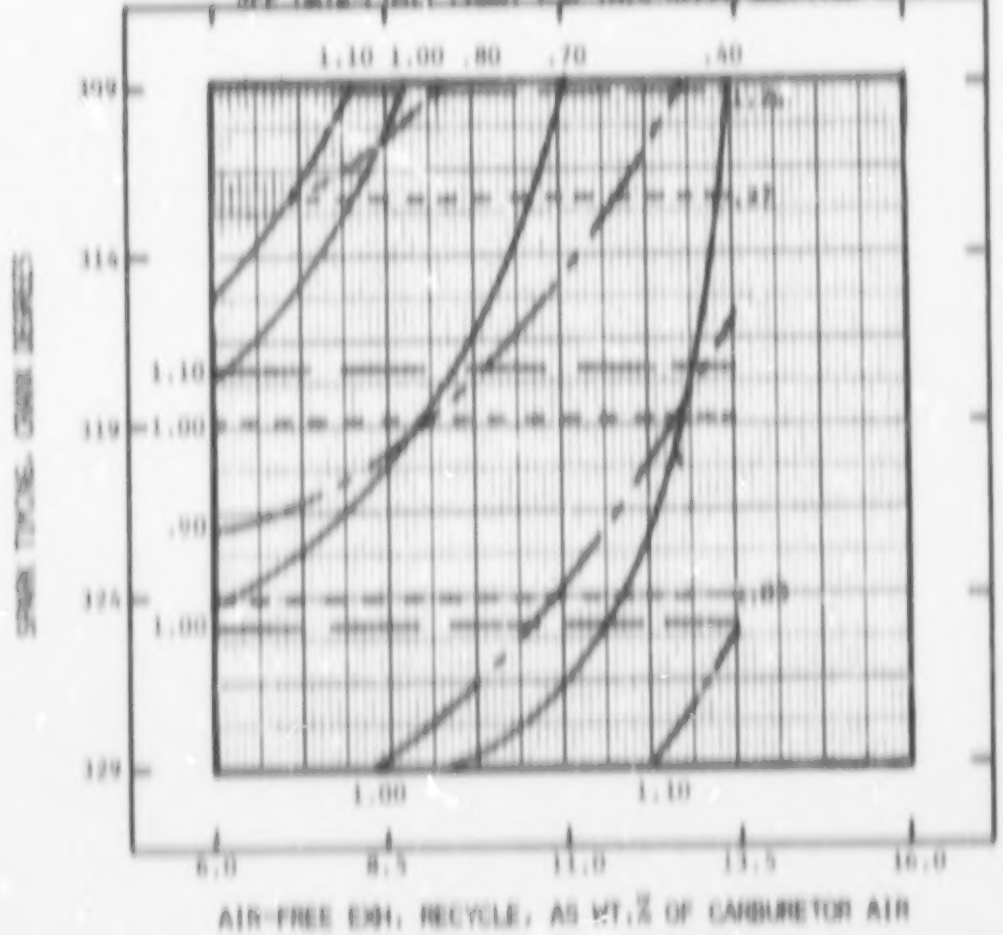
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 1500
CID 170 LB.-FT. TORQUE(1) 30
CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.2306	1904 PPM NO	97.5
REL. # C6H14/HR. (FID)	— — — —	0.1300	626 PPM C6	96.9
REL. # CO/HR.	-------	0.4620	0.21 %	99.0
REL. # FUEL/BHPHR.	— - — -	0.7767		97.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.62

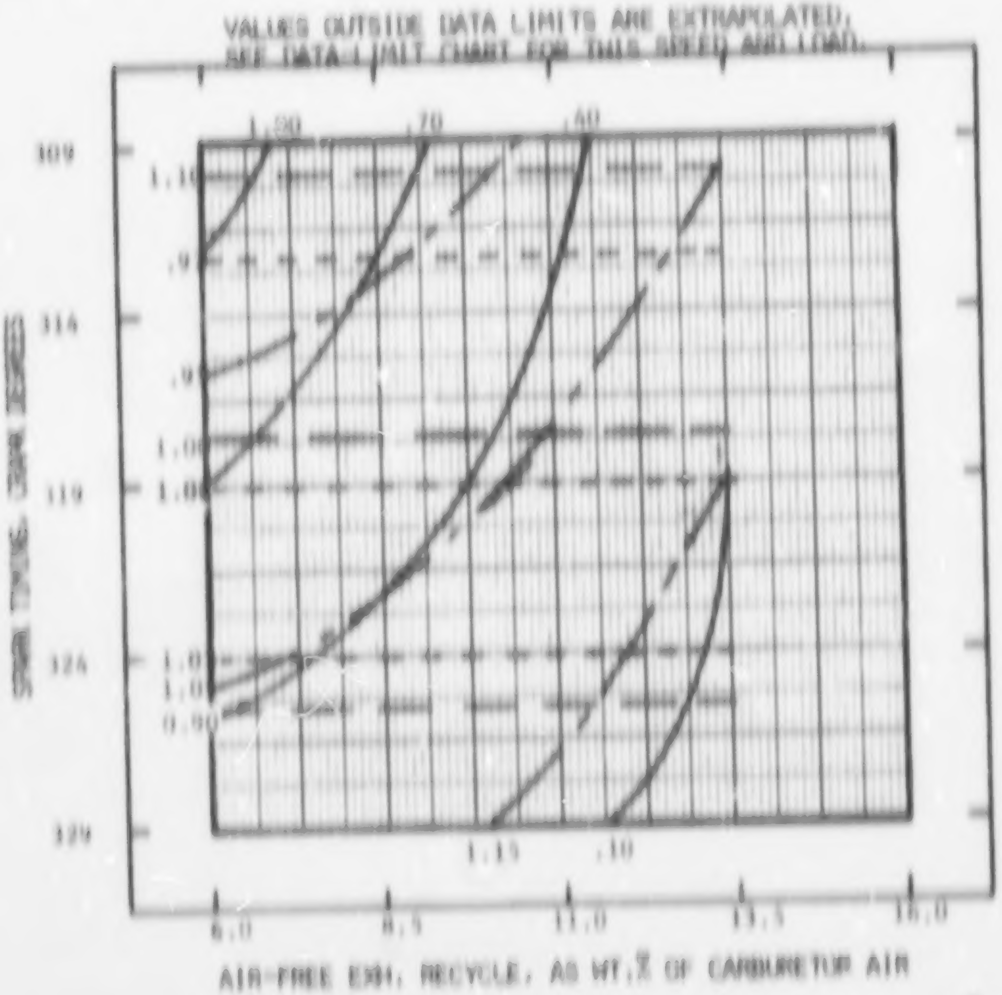
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant	ENGINE RPM 1500
CID 170	LB.-FT. TORQUE(1) 30
CONTROL SYSTEM E-M	A/F RATIO(2) 17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.2506	1905 PPM NO	97.4
REL. # C6H14/HR. (FID)	– – – –	0.1300	526 PPM C6	96.3
REL. # CO/HR.	▬▬▬▬	0.1678	0.21 %	99.0
REL. # FUEL/BHPHR.	– — –	0.7151		97.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.83

USPHS EXHAUST-RECYCLE PROGRAM
DATA LIMIT CHART

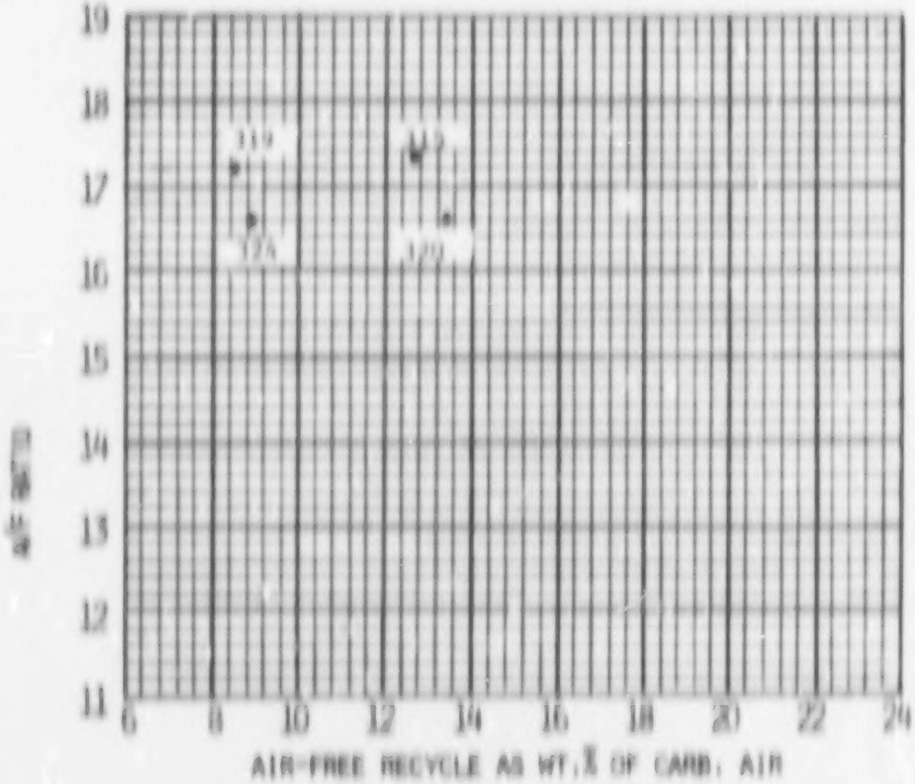
ENGINE: Valiant RPM: 1300 LB.-FT. TQ. 69

MFR'S A/F: 16.6 MFR'S. SPARK: 334 IMAP(1) 21.2 "HG.

CARB. AIR RATE(1) 2.79 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 16.6
Spk.334

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.6A

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

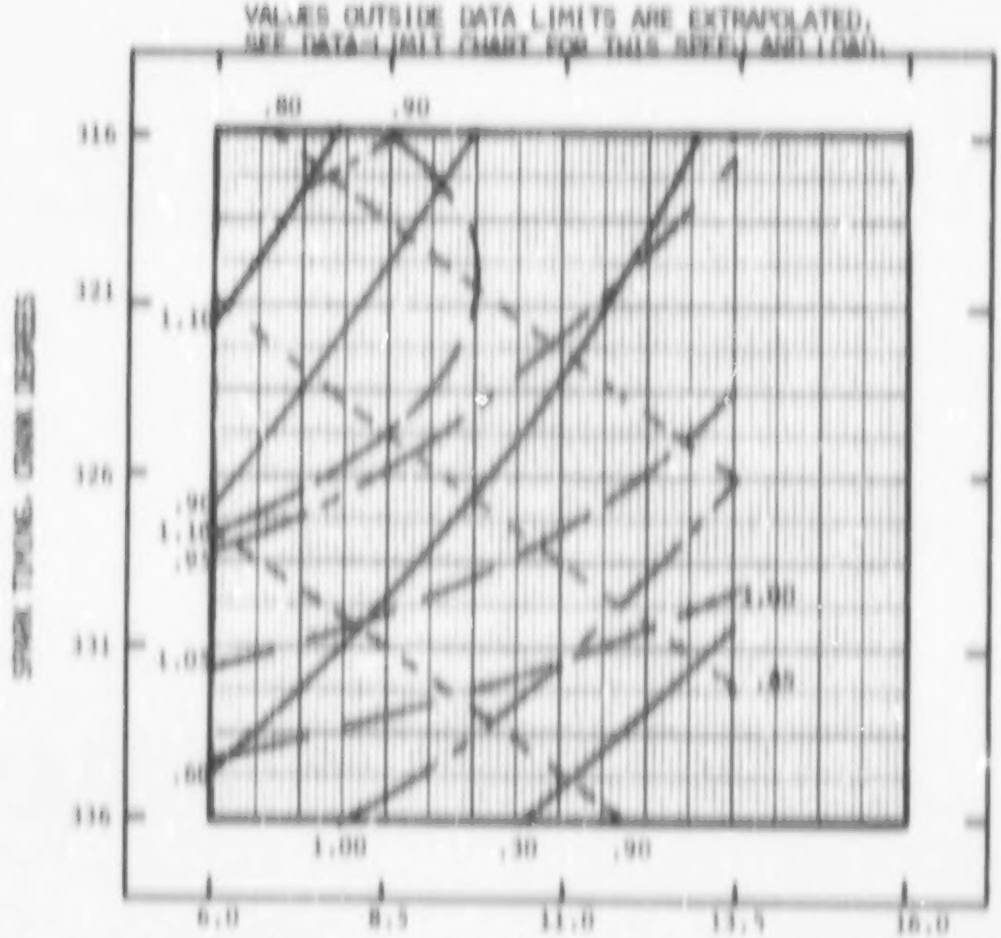
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 1500

CID 170 LB.-FT. TORQUE(1) 69

CONTROL SYSTEM E-M A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.6266	2901 PPM NO	99.6
REL. # C6/HC/HR. (FID)	‒ ‒ ‒ ‒	0.2340	595 PPM C6	80.7
REL. # CO/HR.	········	0.2531	0.19 %	77.6
REL. # FUEL/BHPHR.	‒ ‒‒ ‒	0.5099		89.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA POINTS: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO$_2$ = 15.0%.

FIGURE A2.59

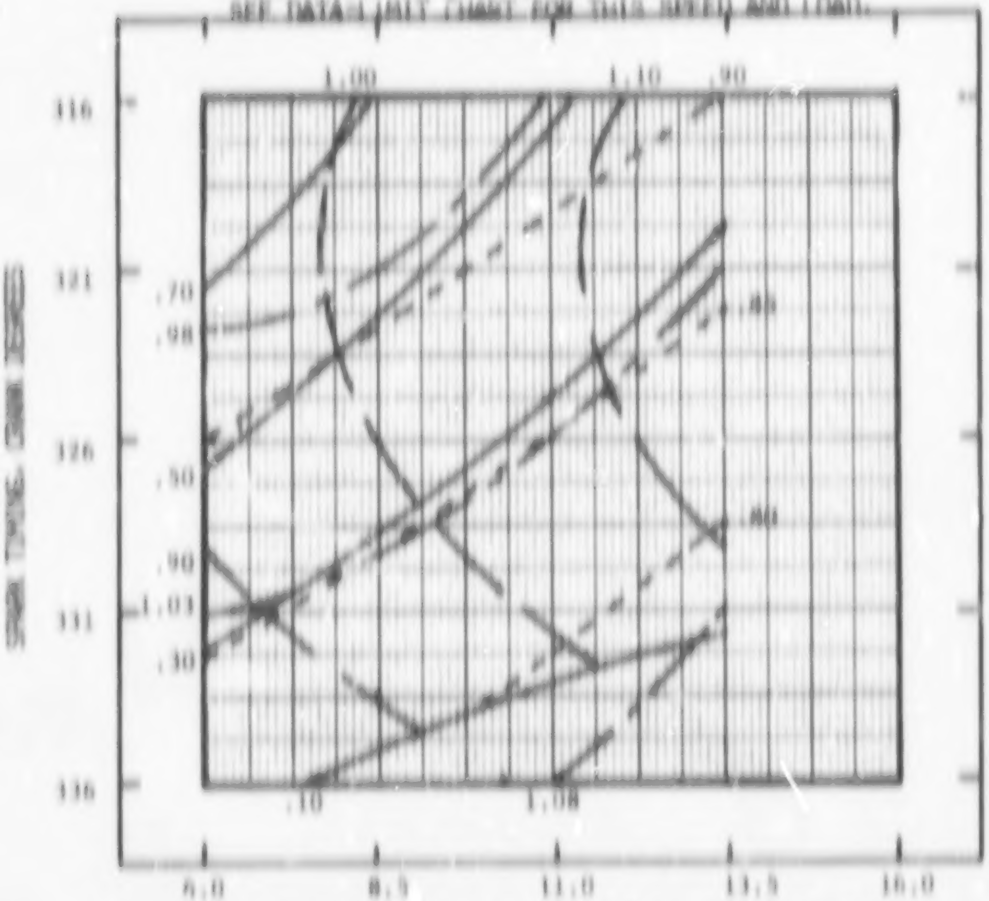
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Valiant	ENGINE RPM	1500
CID	170	LB.-FT. TORQUE(1)	60
CONTROL SYSTEM	E-M	A/F RATIO(2)	17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN
REL. # NO2/HR.	━━━━	0.6266	2903 PPM NO	99.5
REL. # C6H14/HR. (FID)	━ ━ ━ ━	0.2340	595 PPM C6	89.7
REL. # CO/HR.	═══════	0.2531	0.19 %	77.6
REL. # FUEL/BHPHR.	━ ══ ━	0.3099		89.8

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.66

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

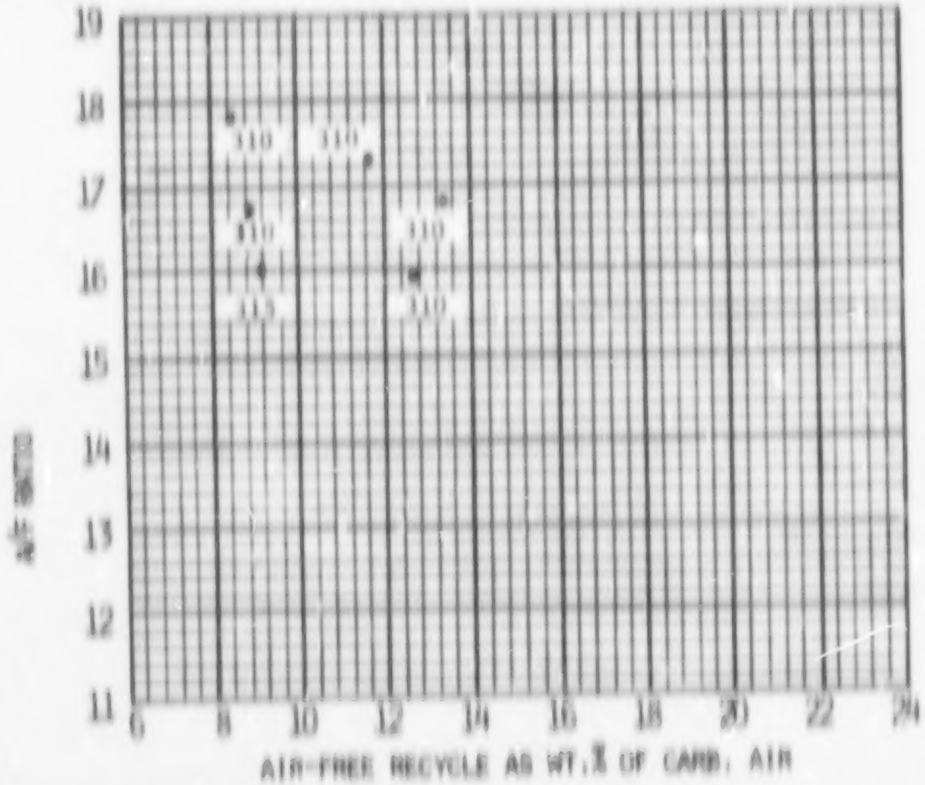
ENGINE: Valiant RPM: 2000 LB.-FT. TQ. 30

MFR'S A/F: 16.6 MFR'S. SPARK: 122 IMAP(1) 15.5 "HG.

CARB. AIR RATE(1) 2.18 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.6
Spk. 122

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.67

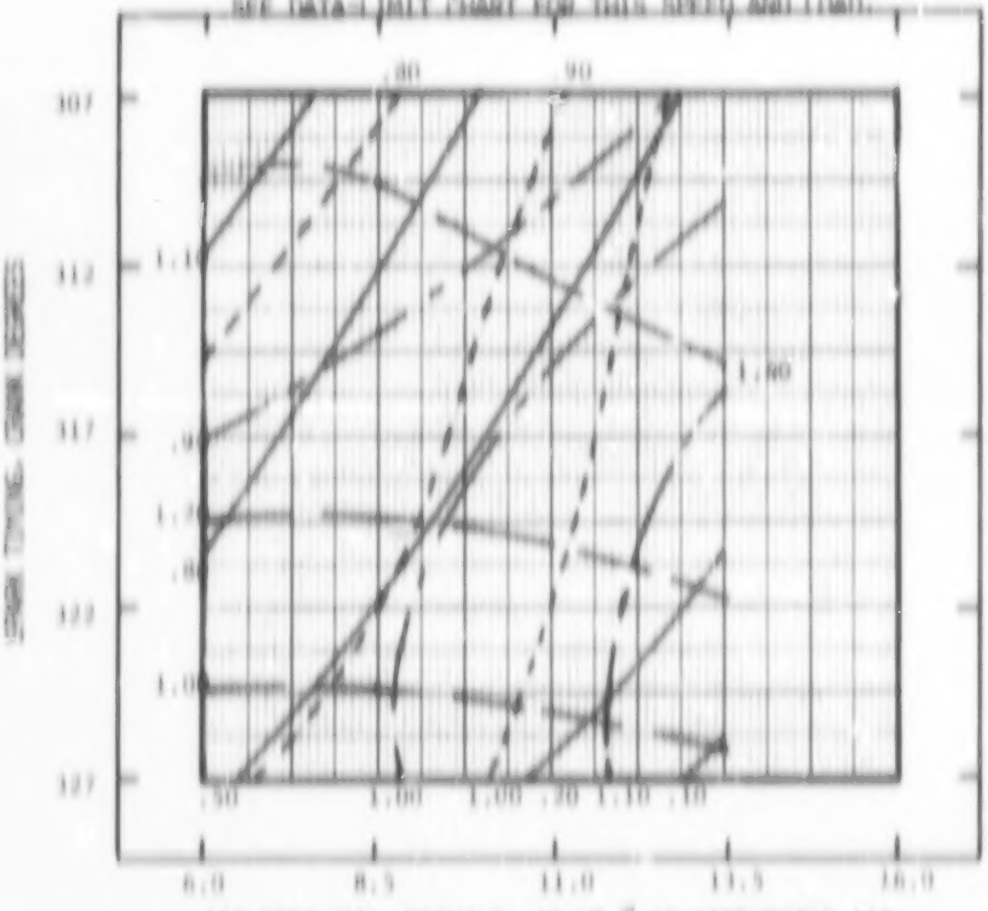
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant
CID 170
CONTROL SYSTEM E-R
ENGINE RPM 2000
LB.-FT. TORQUE(1) 30
A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	0.1560	1981 PPM NO	99.8
REL. # C6/HC/HR. (FID)	= = = =	0.1302	398 PPM C_6	98.0
REL. # CO/HR.	=======	0.2773	0.25 %	69.2
REL. # FUEL/BHPHR.	= == =	0.7259		93.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.68

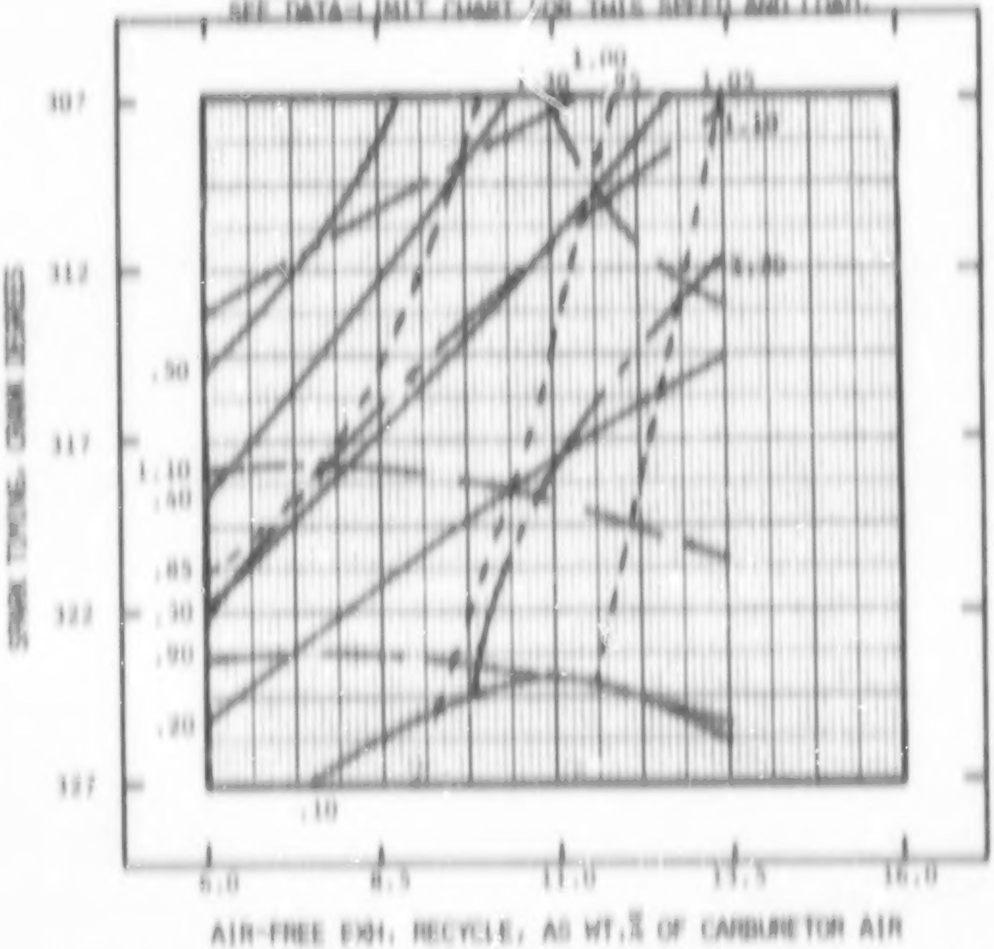
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant
ENGINE RPM 2000
CID 170
LB.-FT. TORQUE(1) ____
CONTROL SYSTEM E-M
A/F RATIO(2) 17.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.1560	1981 PPM NO	99.8
REL. # C6/HR. (FID)	— — — —	0.1302	398 PPM C6	98.0
REL. # CO/HR.	- - - - - - -	0.2773	0.25 %	69.2
REL. # FUEL/BHPHR.	— — —	0.7269		92.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

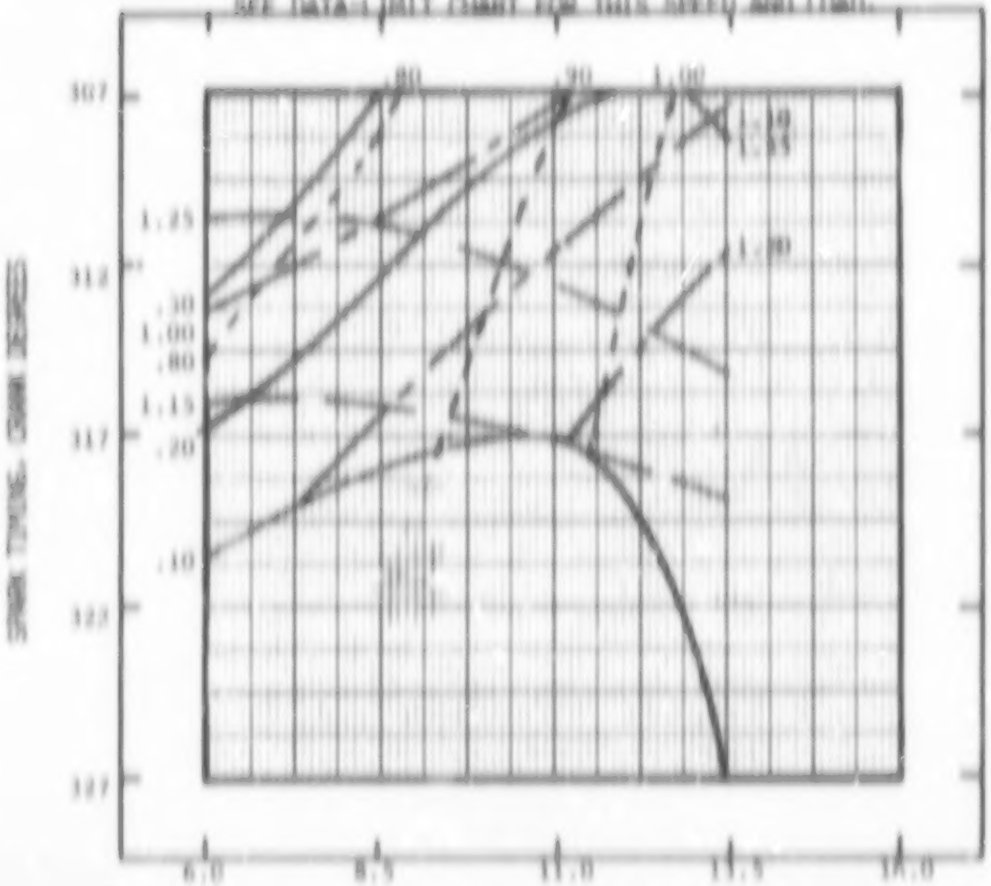
FIGURE A2.12
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant
ENGINE RPM 2000
CID 170
LB.-FT. TORQUE(1) 30
CONTROL SYSTEM E-M
A/F RATIO(2) 17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.3560	1981 PPM NO	99.8
REL. # C_6 HC/HR. (FID)	– – – –	0.1302	398 PPM C_6	98.0
REL. # CO/HR.	- - - - -	0.2773	0.25 %	69.2
REL. # FUEL/BHPHR.	– — –	0.7269		92.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.70

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

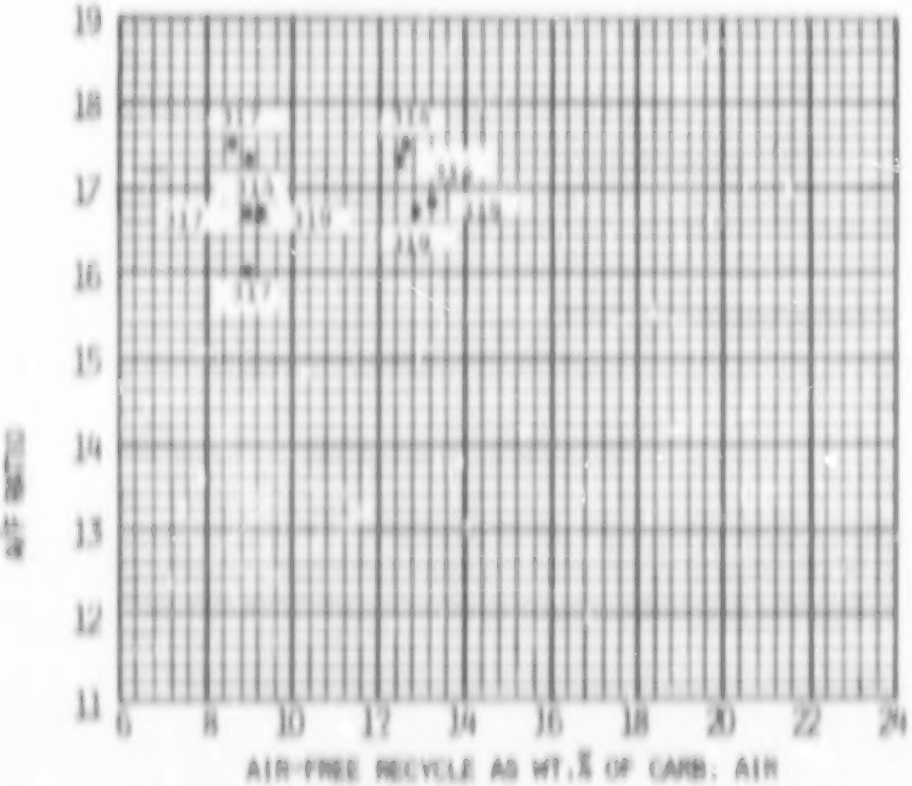
ENGINE: Valiant RPM: 2000 LB.-FT. TQ. 30

MFR'S A/F: 16.7 MFR'S. SPARK: 122 IMAP(1) 18.2 "HG.

CARB. AIR RATE(1) 2.26 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.7
Spk. 122-129

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A1.71

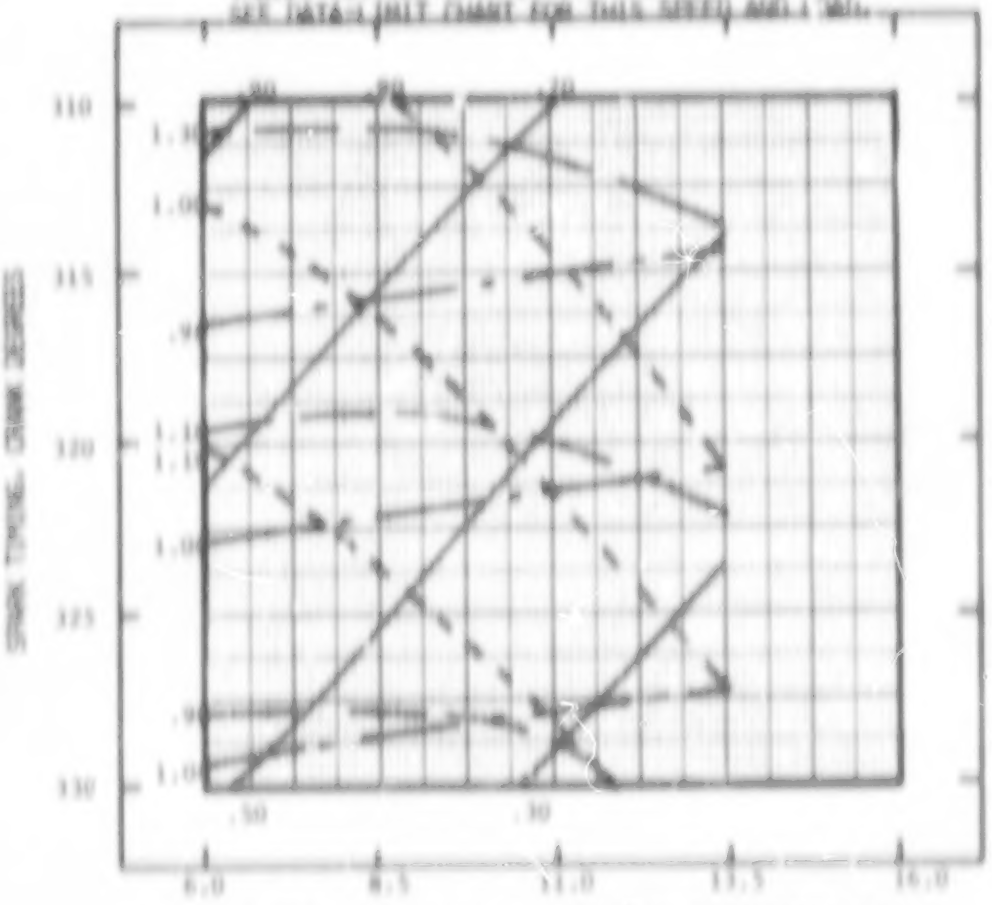
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2000
CID 170 LB.-FT. TORQUE(1) 30
CONTROL SYSTEM E-M A/F RATIO(2) 16.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	0.7973	3293 PPM NO	93.2
REL. # C6HC/HR. (FID)	– – – –	0.2030	436 PPM C6	91.5
REL. # CO/HR.	++++++	0.3667	0.23 %	57.3
REL. # FUEL/BHPHR.	– —– –	0.3882		78.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK. NO RECYCLE. CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A7.73

USPHS EXHAUST-RECYCLE PROGRAM

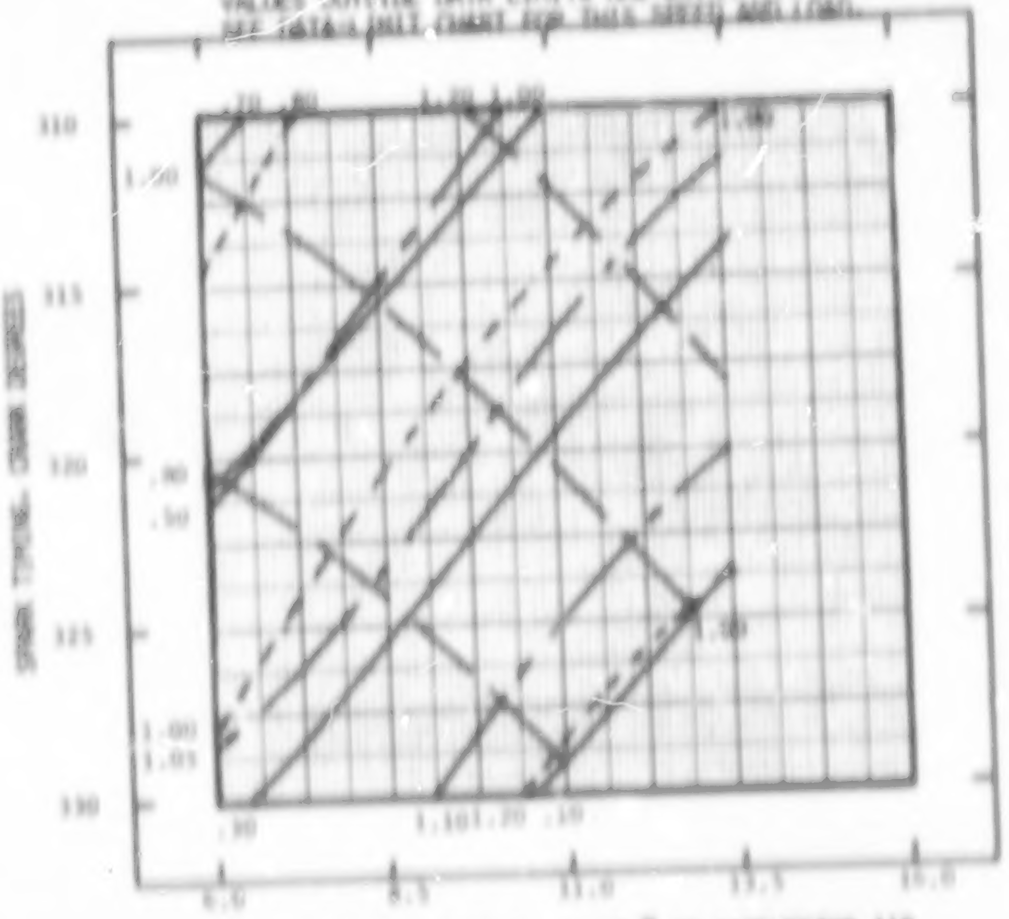
STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2000

CID 170 LB.-FT. TORQUE(1) 30.

CONTROL SYSTEM E-R A/F RATIO(2) 12.3



VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED; SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.

AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.7473	1293 PPM NO	93.2
REL. # C6H14/HR. (FID)	— — —	0.2010	156 PPM C6	93.5
REL. # CO/HR.	- - - - - -	0.3667	0.21 %	57.1
REL. # FUEL/BHPHR.	— - —	0.5882		18.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

[illegible]

[illegible]

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

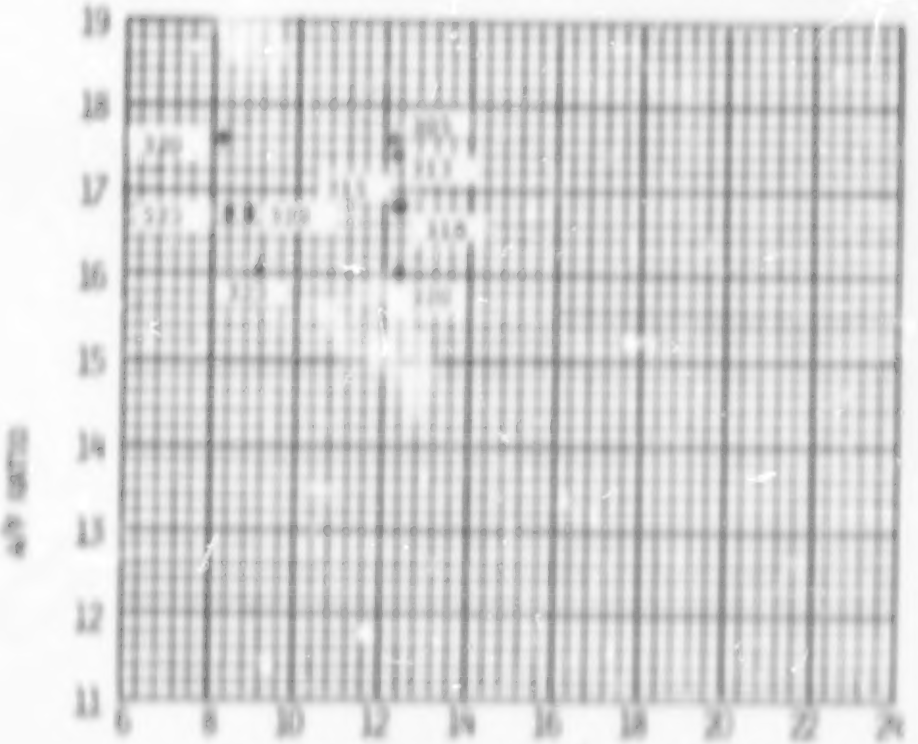
ENGINE: Valiant RPM: 2000 LB.-FT. TQ. 49

MFR'S A/F: 14.7 MFR'S. SPARK: 110 IMAP(1) 21.7 "HG.

CARB. AIR RATE(1) 3.90 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.7-17.6
Spk. 120-145

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A7.75

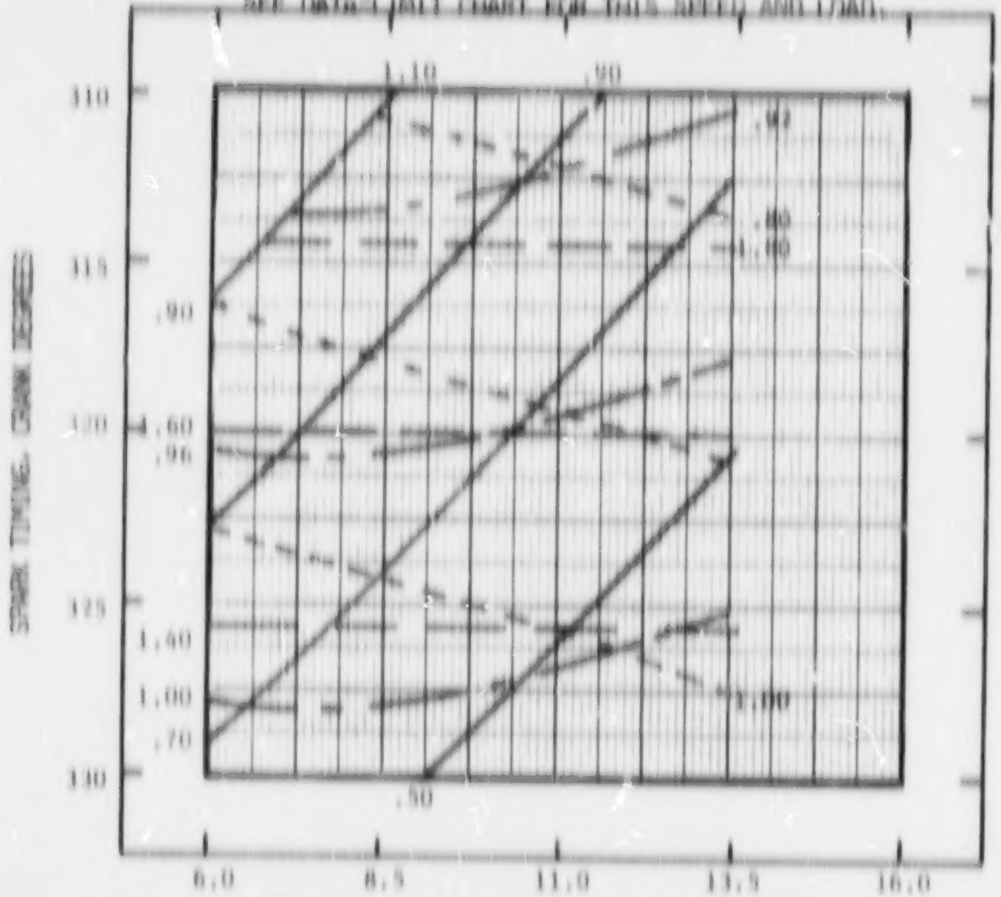
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Valiant	ENGINE RPM	2000
CID	170	LB.-FT. TORQUE(1)	69
CONTROL SYSTEM	E-R	A/F RATIO(2)	16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬▬	0.9597	3173 PPM NO	97.5
REL. # C6HC/HR. (FID)	– – – –	0.1780	323 PPM C6	90.3
REL. # CO/HR.	········	0.5336	0.29 %	87.2
REL. # FUEL/BHPHR.	‒ ▬ ‒	0.5257		80.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.75

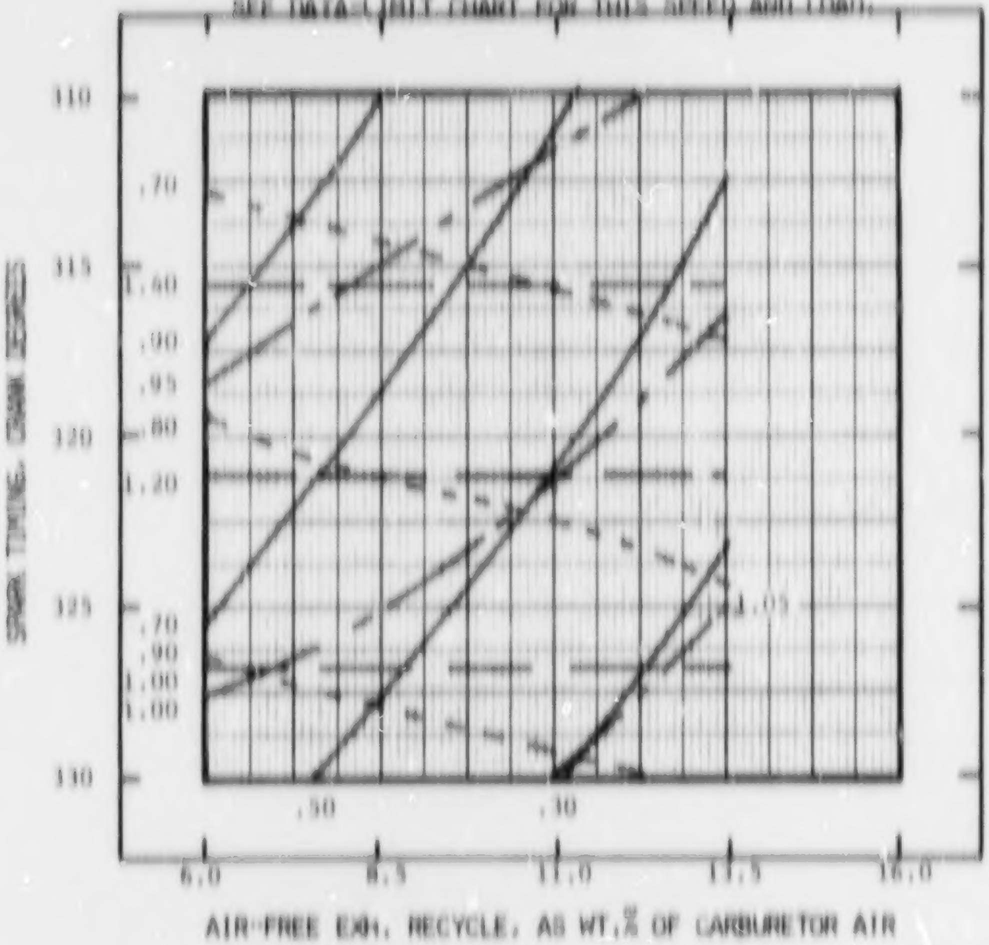
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Valiant	ENGINE RPM	2000
CID	170	LB.-FT. TORQUE(1)	69
CONTROL SYSTEM	E-M	A/F RATIO(2)	17.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	————	0.9597	1173 PPM NO	97.5
REL. # C6HC/HR. (FID)	- - - -	0.1780	121 PPM C6	90.3
REL. # CO/HR.	········	0.5336	0.29 %	87.2
REL. # FUEL/BHPHR.	— — —	0.5257		80.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.76

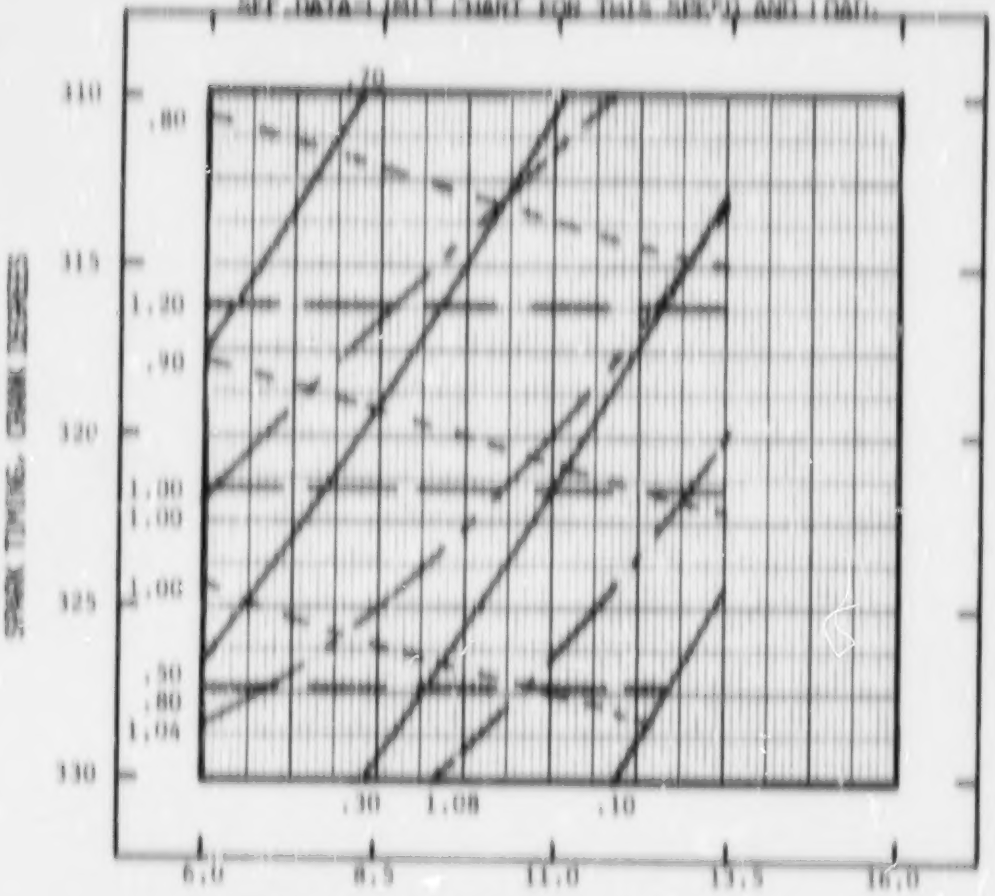
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2000
CID 170 LB.-FT. TORQUE(1) 69
CONTROL SYSTEM S-H A/F RATIO(2) 17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.9597	3173 PPM NO	97.5
REL. # C6HC/HR. (FID)	= = = =	0.1780	123 PPM C6	90.1
REL. # CO/HR.	-------	0.5336	0.29 %	87.2
REL. # FUEL/BHPHR.	= —— =	0.5257		80.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.77

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

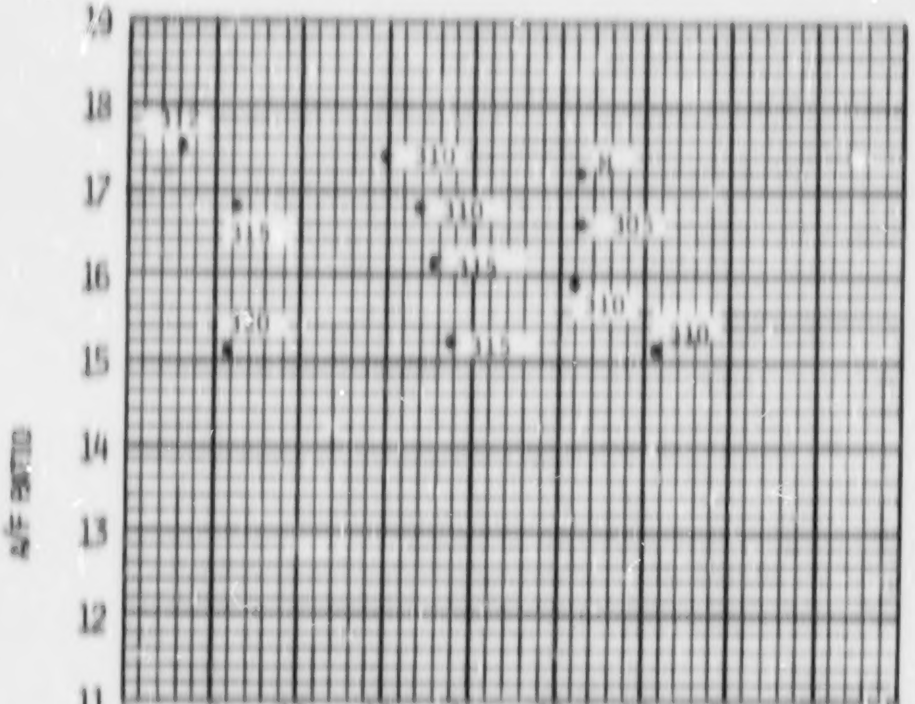
ENGINE: Valiant RPM: 2500 LB.-FT. TQ. 47

MFR'S A/F: 16.8 MFR'S. SPARK: 120 IMAP(1) 17.3 "HG.

CARB. AIR RATE(1) 3.71 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED$^{(2)}$ AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.6-17.6
Spk. 120-130

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.78

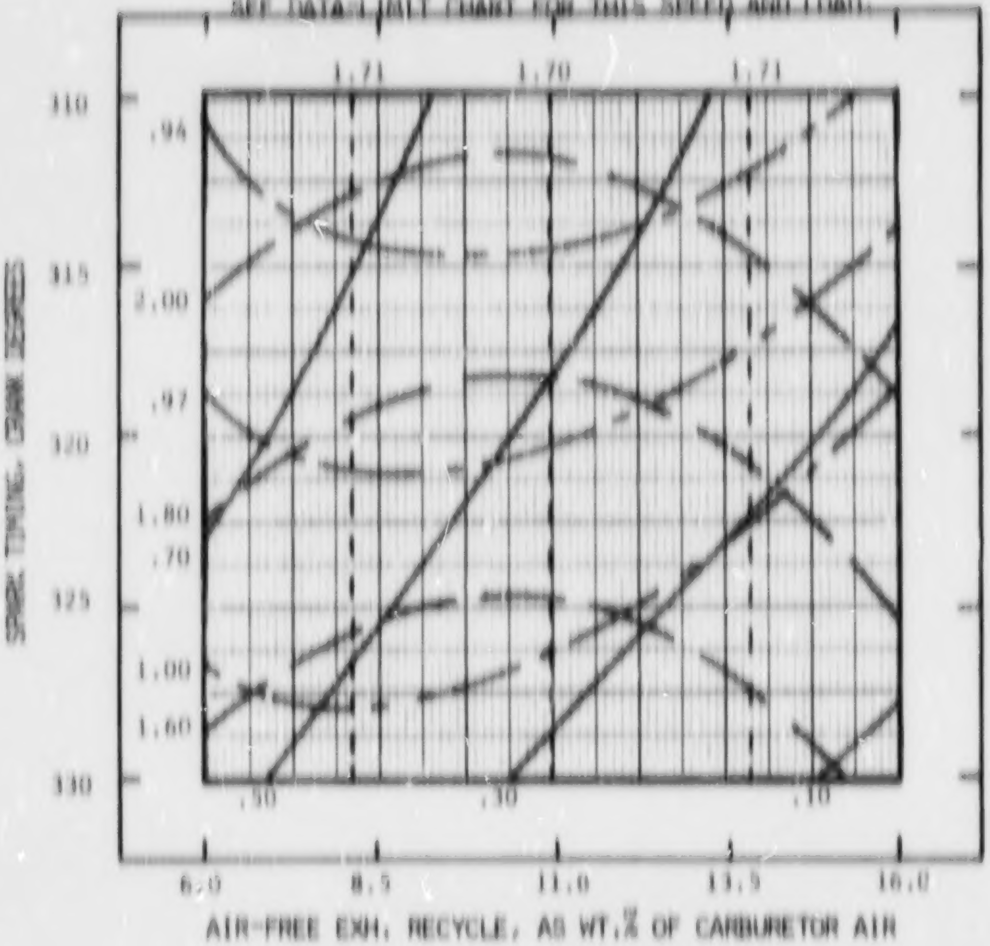
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2500
CID 170 LB.-FT. TORQUE(1) 67
CONTROL SYSTEM E.R A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.9532	3189 PPM NO	97.7
REL. # C_6C/HR. (FID)	‒ ‒ ‒ ‒	0.1456	268 PPM C_6	97.0
REL. # CO/HR.	-------	0.5916	0.32 %	93.6
REL. # FUEL/BHPHR.	‒ — ‒	0.6157		95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

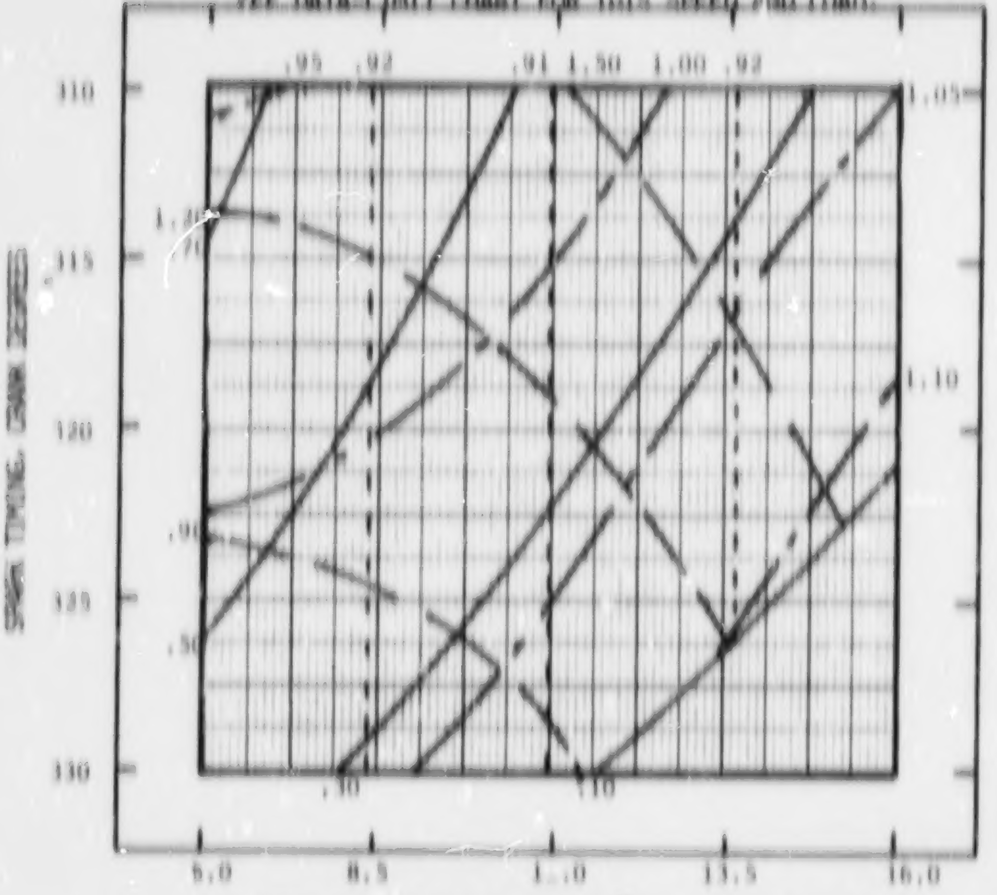
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.79

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant
ENGINE RPM 2500
CID 170
LB.-FT. TORQUE(1) 47
CONTROL SYSTEM E-R
A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	——	0.9512	3189 PPM NO	97.7
REL. # C6HC/HR. (FID)	– – – –	0.1656	268 PPM C6	97.0
REL. # CO/HR.	-·-·-·-	0.5916	0.32 %	93.4
REL. # FUEL/BHPHR.	– — –	0.6157		95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.80

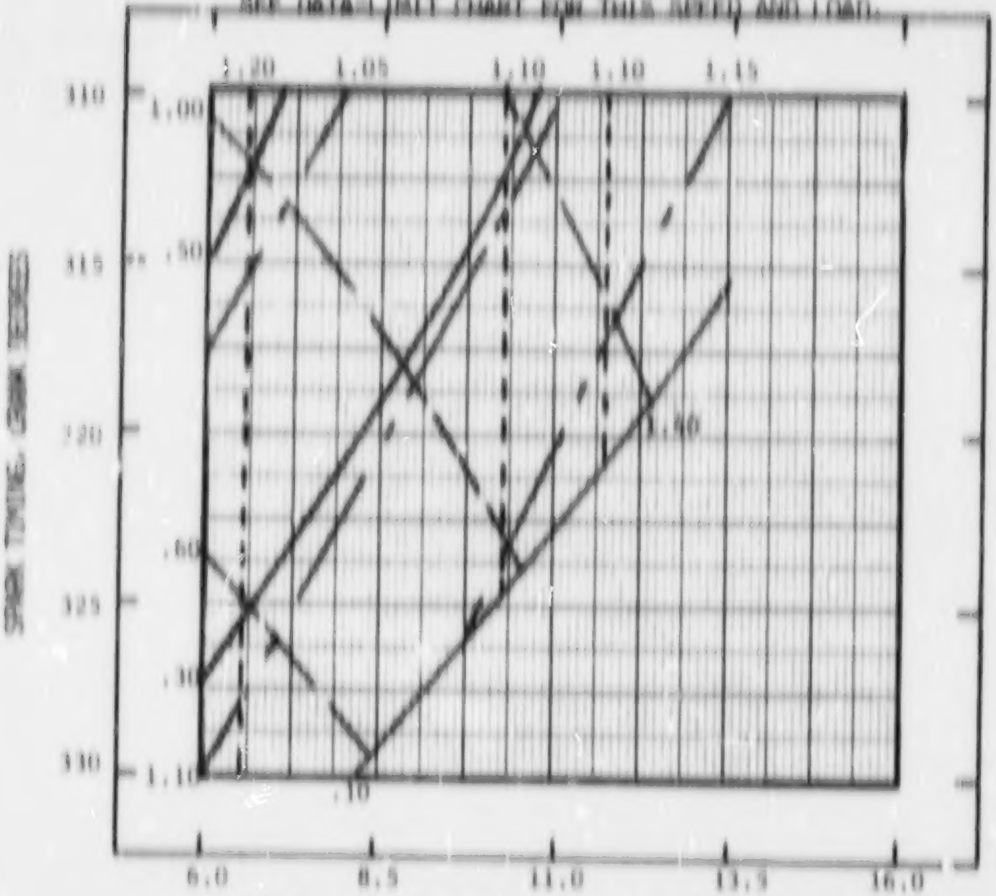
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2500
CID 170 LB.-FT. TORQUE(1) 47
CONTROL SYSTEM E-M A/F RATIO(2) 17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.9512	1189	PPM NO	97.7
REL. # C6HC/HR. (FID)	– – – –	0.1656	268	PPM C6	97.0
REL. # CO/HR.	········	0.5916	0.32	%	93.4
REL. # FUEL/BHPHR.	–·– –	0.6157			95.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.81

USPHS EXHAUST-RECYCLE PROGRAM
DATA LIMIT CHART

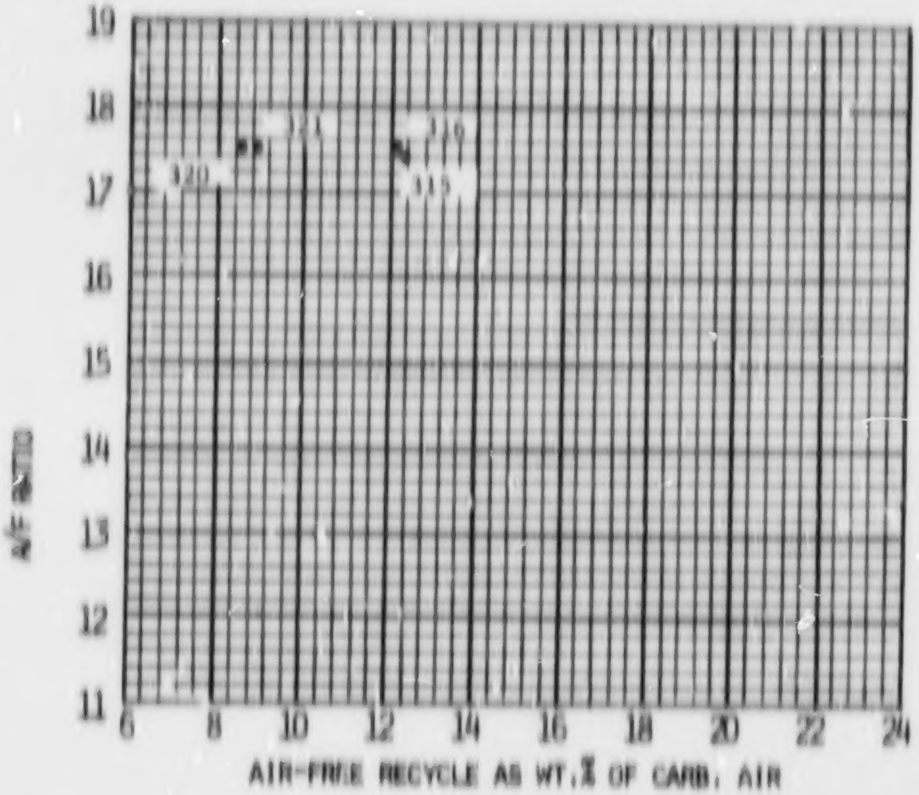
ENGINE: Valiant RPM: 2500 LB.-FT. TQ: 69

MFR'S A/F: 16.8 MFR'S. SPARK: 326 IMAP(1) 21.6 "HG.

CARB. AIR RATE(1) 4.65 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.8-17.6
Spk. 326-330

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.82

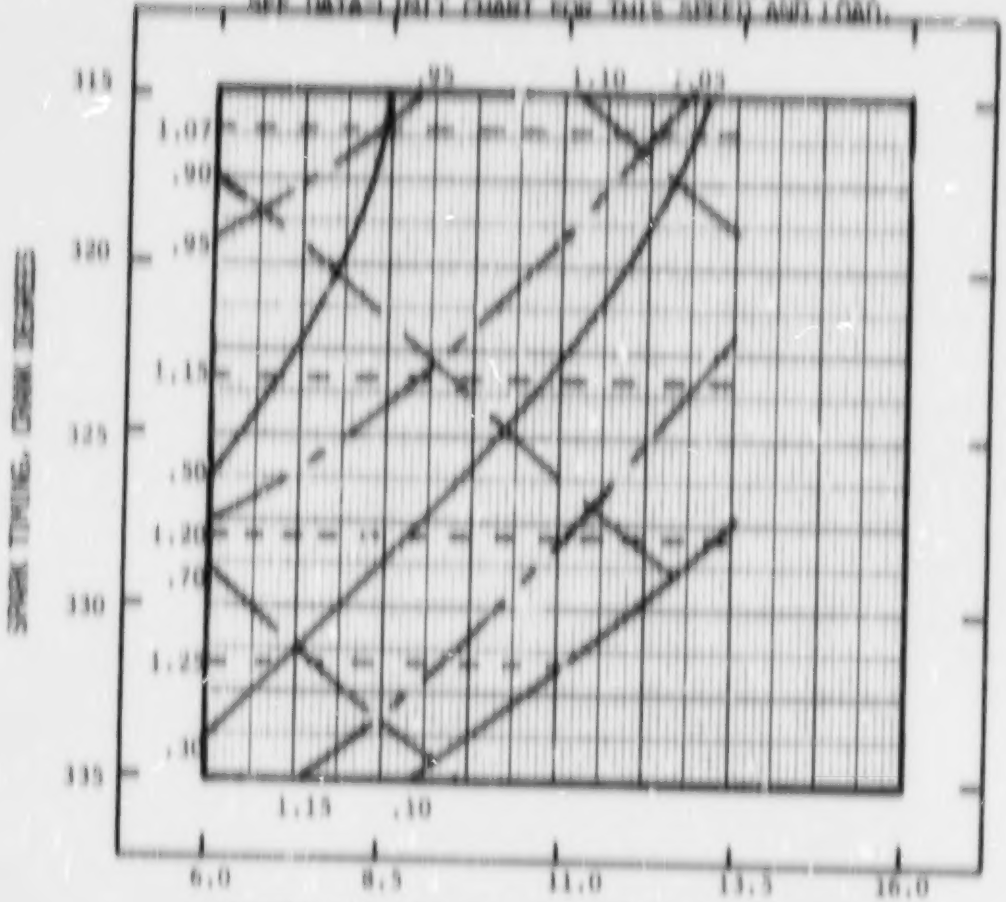
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 2500
CID 170 LB.-FT. TORQUE(1) 69
CONTROL SYSTEM E-H A/F RATIO(2) 17.1

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3691	3608 PPM NO	99.6
REL. # C6/HC/HR. (FID)	— — — —	0.1411	205 PPM C6	68.6
REL. # CO/HR.	--------	0.7580	0.33 %	79.7
REL. # FUEL/BHPHR.	— —— —	0.5293		80.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.83

USPHS EXHAUST-RECYCLE PROGRAM
DATA LIMIT CHART

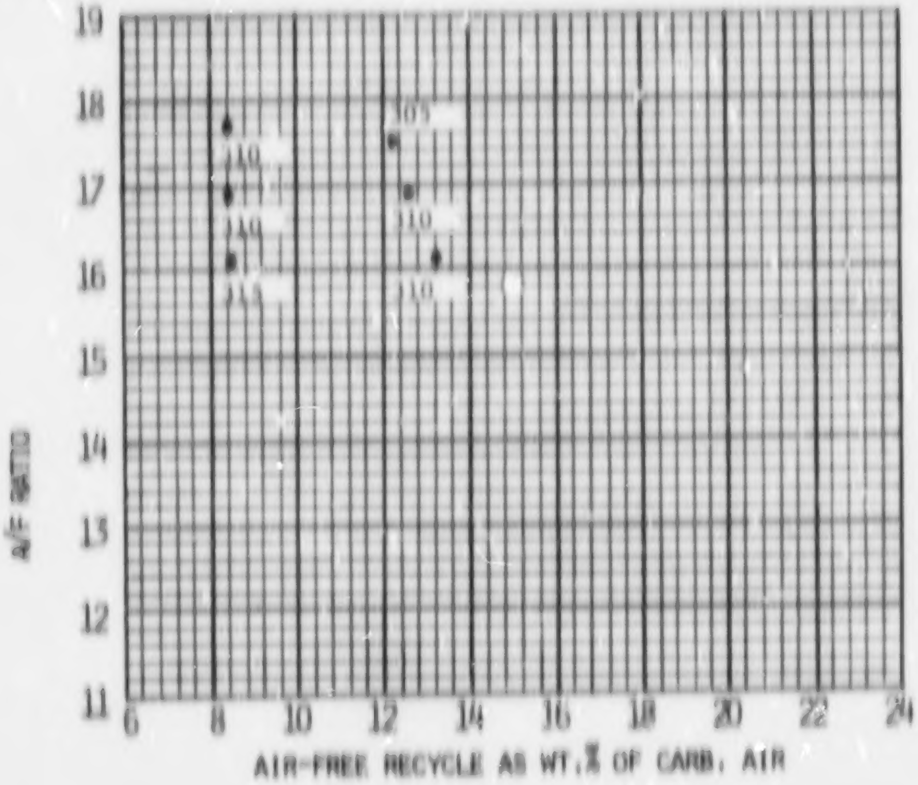
ENGINE: Valiant RPM: 1000 LB.-FT. TQ. 49

MFR'S A/F: 16.9 MFR'S. SPARK: 324 IMAP(1) 21.6 "HG.

CARB. AIR RATE(1) 5.67 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 16.9-17.9
Spk. 323-333

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.84

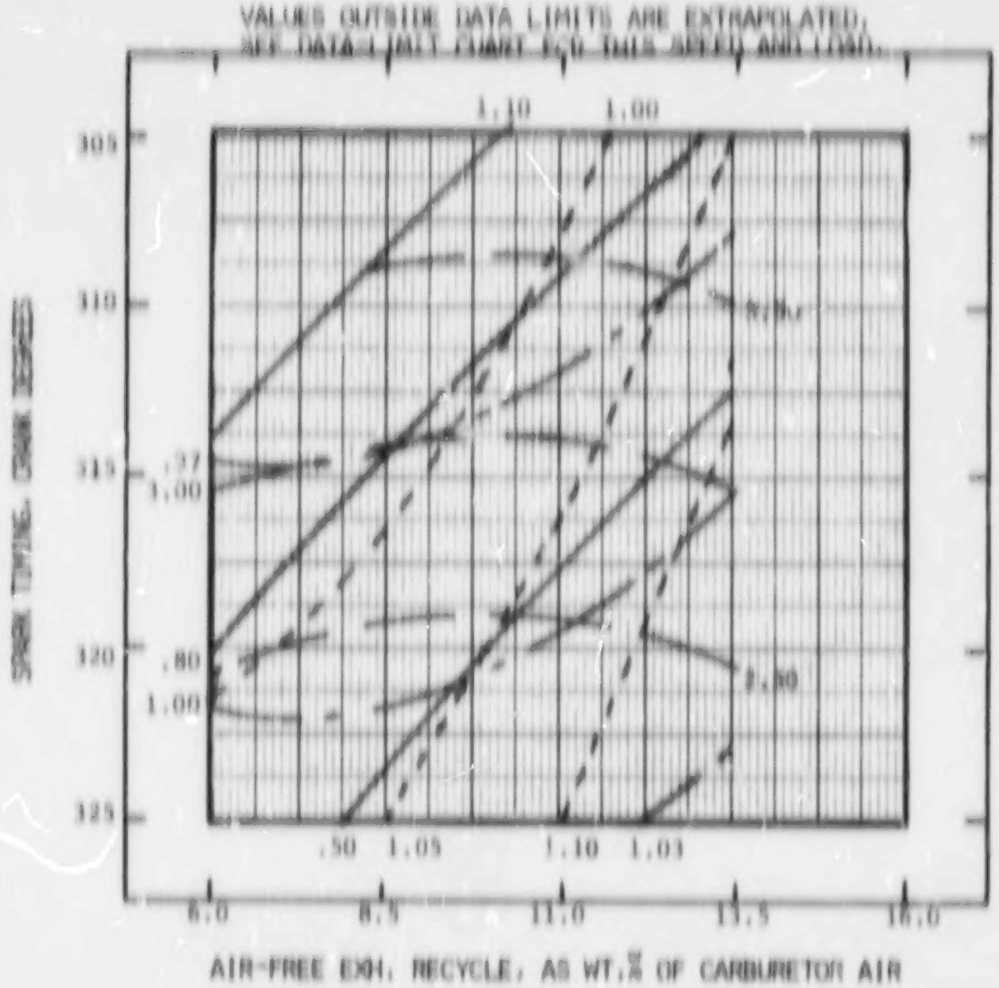
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 3000
CID 170 LB.-FT. TORQUE(1) 69
CONTROL SYSTEM E-M A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6707	3623 PPM NO	98.2
REL. # C6HC/HR. (FID)	– – – –	0.0702	85 PPM C6	98.2
REL. # CO/HR.	-------	0.9101	0.32 %	57.8
REL. # FUEL/BHPHR.	– — –	0.5426		96.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: Spindt Equation
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.85

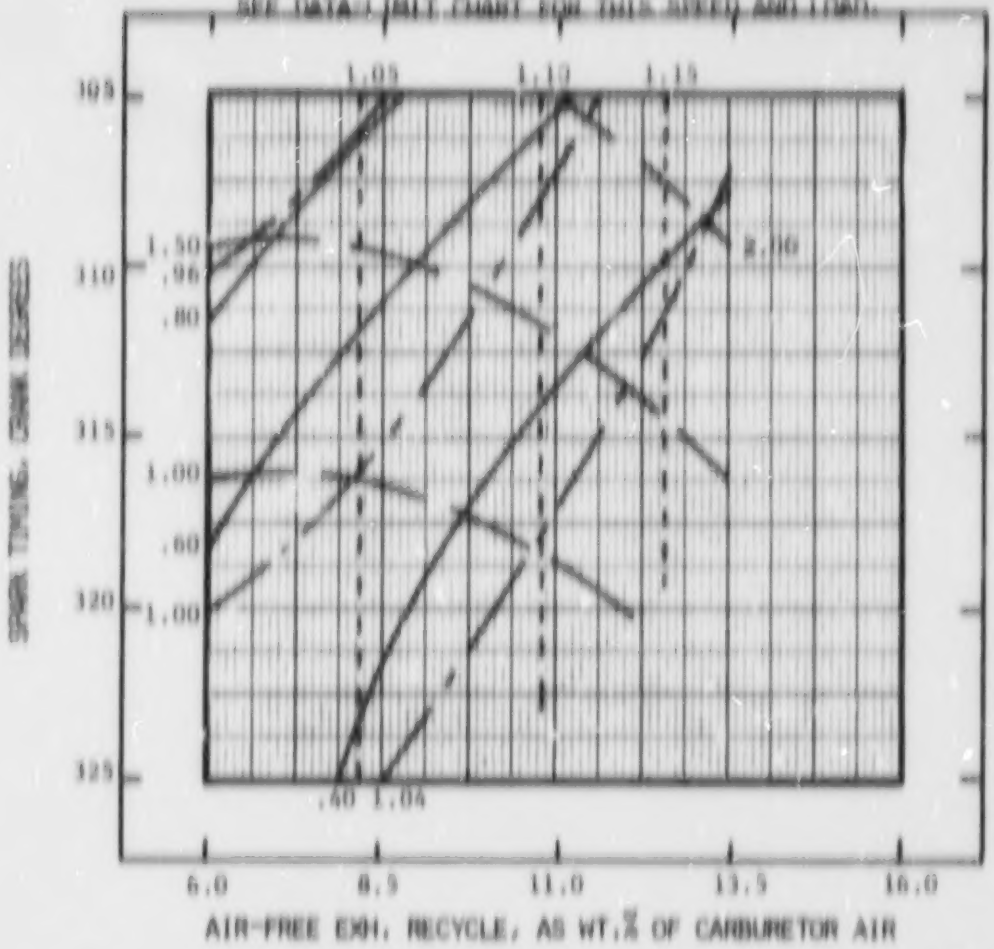
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Valiant	ENGINE RPM	2000
CID	170	LB.-FT. TORQUE(1)	69
CONTROL SYSTEM	E-H	A/F RATIO(2)	17.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6707	1023 PPM NO	98.2
REL. # C6HC/HR. (FID)	- - - -	0.0702	85 PPM C6	98.2
REL. # CO/HR.	--------	0.9101	0.32 %	57.6
REL. # FUEL/BHPHR.	- — -	0.5426		96.4

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.86

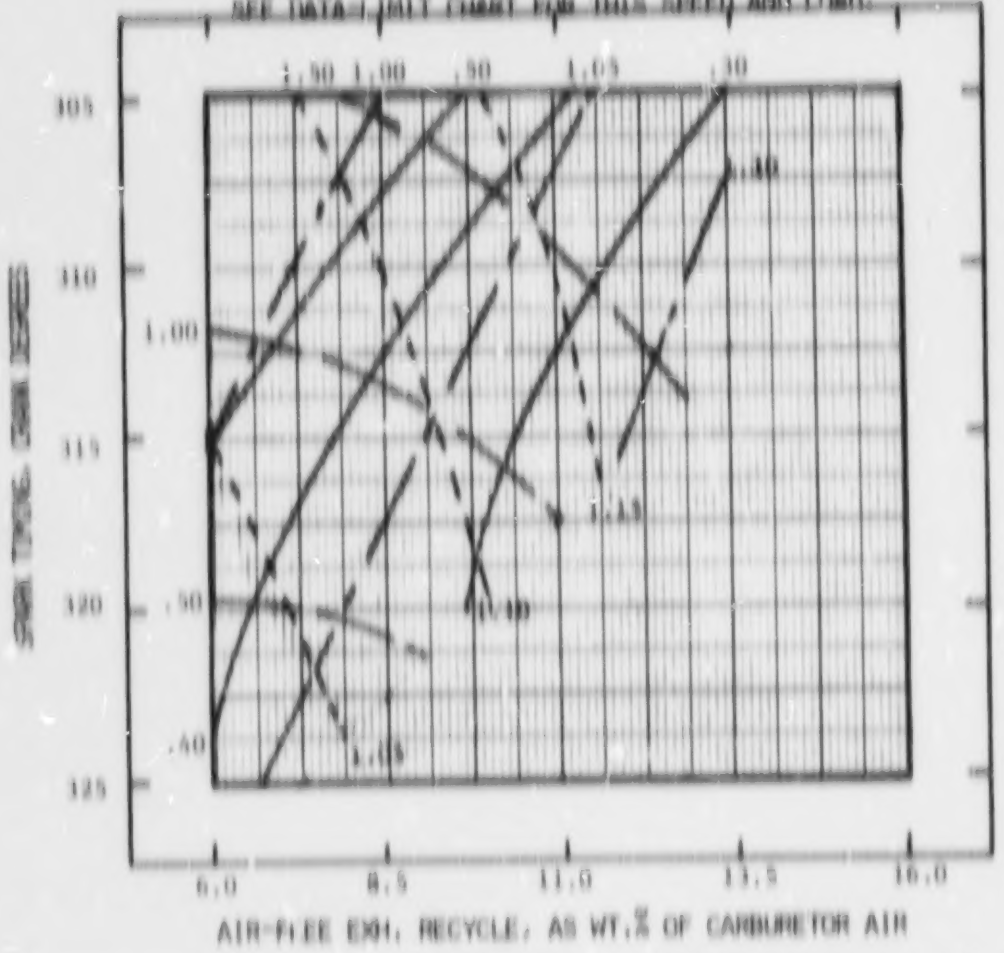
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Valiant ENGINE RPM 3000
CID 170 LB.-FT. TORQUE(1) 69
CONTROL SYSTEM E.R. A/F RATIO(2) 17.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.6707	1621	PPM NO	98.2
REL. # C6HC/HR. (FID)	- - - -	0.0702	88	PPM C6	98.2
REL. # CO/HR.	-------	0.9101	0.37	%	57.8
REL. # FUEL/BHPHR.	- — -	0.5524			96.4

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: Spindt Equation

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.87

USPHS EXHAUST-RECYCLE PROGRAM

DATA-LIMIT CHART

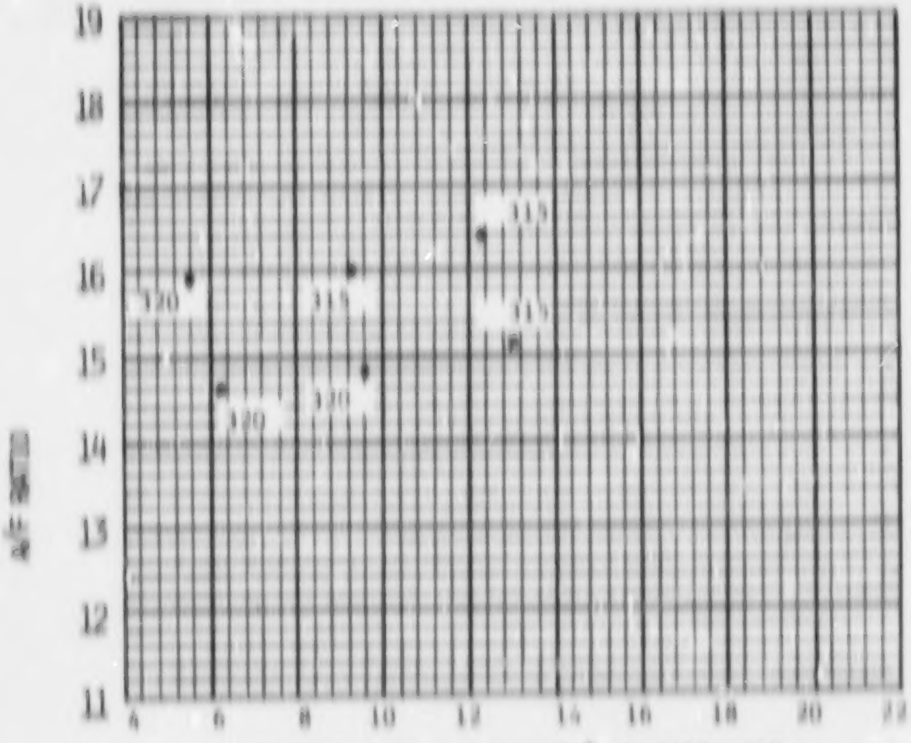
ENGINE: Ford RPM: 1500 LB.-FT. TQ. 35

MFR'S A/F: 15.0 MFR'S. SPARK: 130 IMAP(1) 10.9 "HG.

CARB. AIR RATE(1) 2.16 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 14.9-15.1
Spk. 30

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

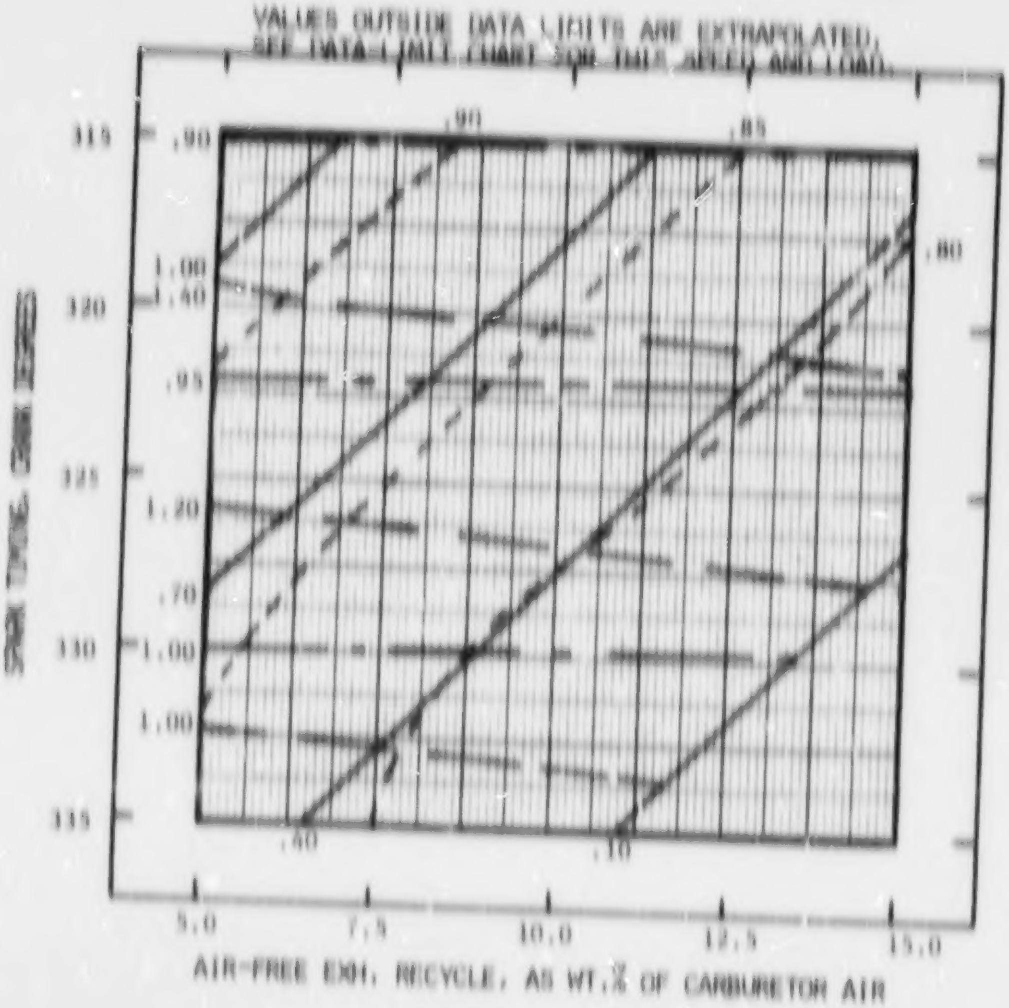
(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.98

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 1500
CID 289
LB.-FT. TORQUE(1) 15
CONTROL SYSTEM A-1
A/F RATIO(2) 15.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.2200	1186 PPM NO	94.5
REL. # C6HC/HR. (FID)	— — —	0.2798	820 PPM C6	92.5
REL. # CO/HR.	-·-·-	0.4297	0.38 %	96.2
REL. # FUEL/BHPHR.	— — —	0.8721		94.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carburetor Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MPR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.89

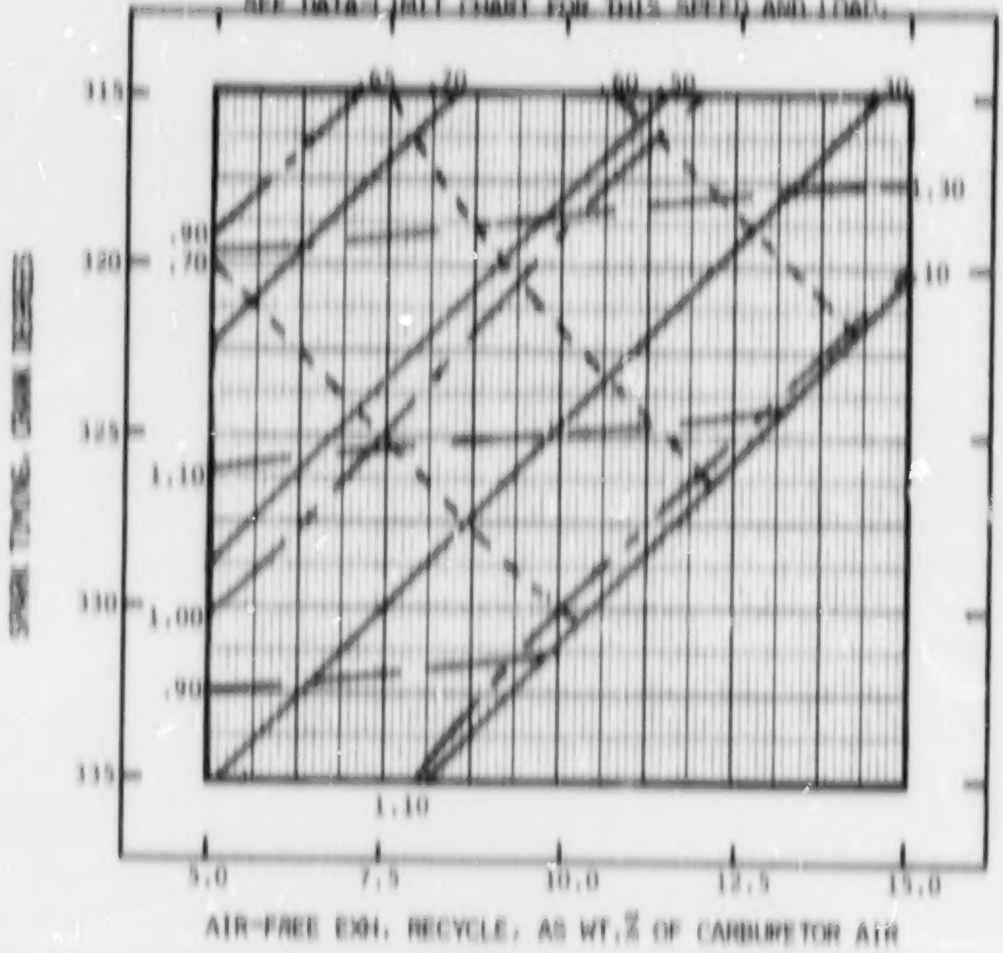
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 1500
CID 289 LB.-FT. TORQUE(1) 15
CONTROL SYSTEM A-1 A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.2200	1186 PPM NO	94.5
REL. # C6HC/HR. (FID)	— — — —	0.2798	829 PPM C6	92.5
REL. # CO/HR.	┄┄┄┄	0.6297	0.38 %	96.2
REL. # FUEL/BHPHR.	— —— —	0.8721		94.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.90

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

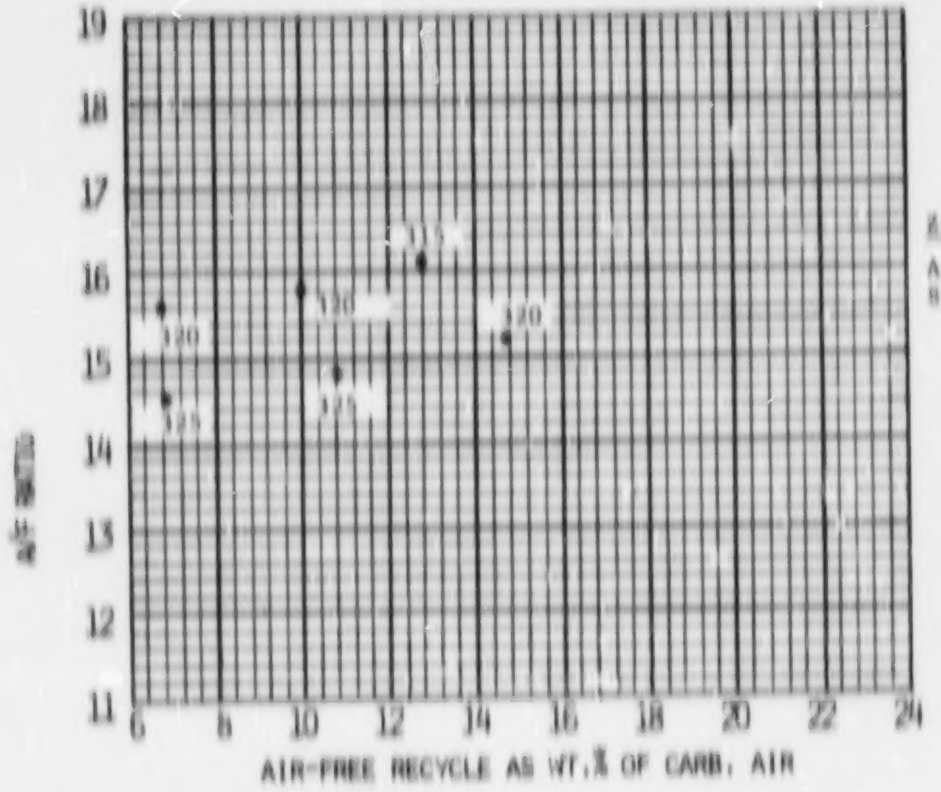
ENGINE: Ford RPM: 1500 LB.-FT. TQ. 30

MFR'S A/F: 15.0 MFR'S. SPARK: 330 IMAP(1) 12.6 "HG.

CARB. AIR RATE(1) 2.55 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



AIR-FREE RECYCLE AS WT.% OF CARB. AIR

Data for
Zero Recycle
A/F 14.0-15.2
Spk. 330

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.91

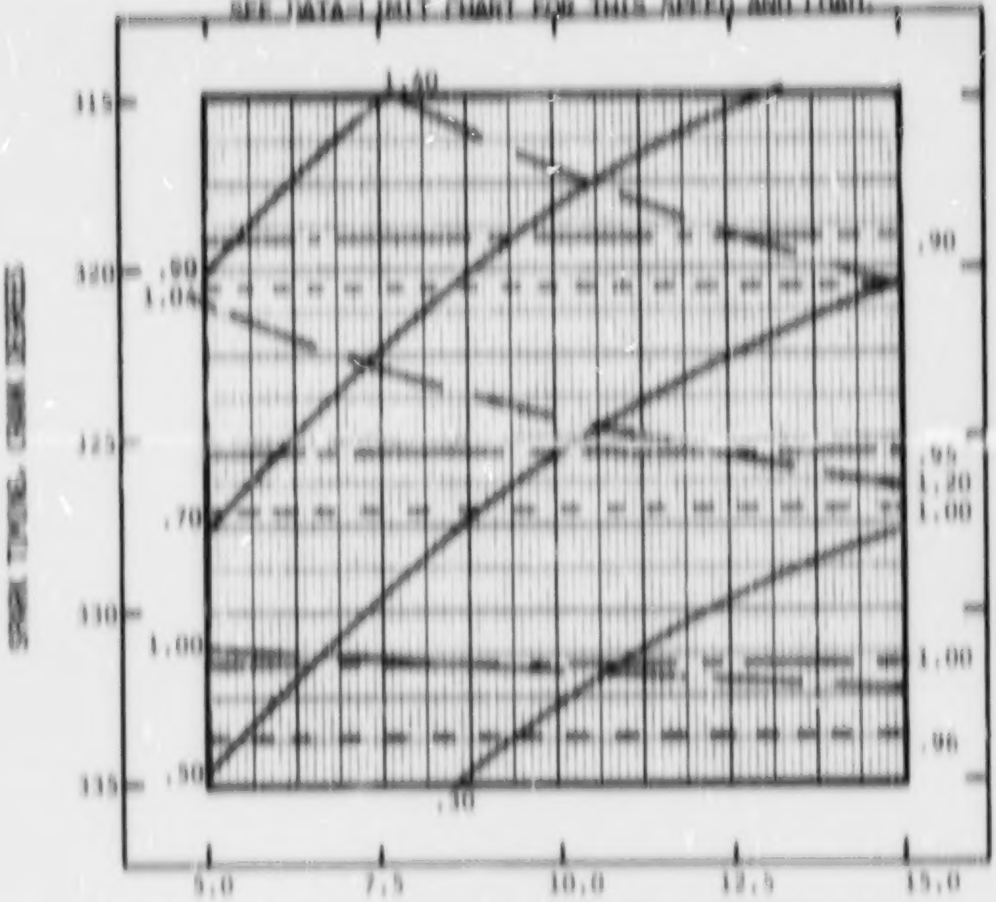
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford — ENGINE RPM 1500
CID 289 — LB.-FT. TORQUE(1) 30
CONTROL SYSTEM A-1 — A/F RATIO(2) 15.8

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.3963	1839 PPM NO	98.8
REL. # C6HC/HR. (FID)	─ ─ ─ ─	0.3793	967 PPM C6	97.3
REL. # CO/HR.	----- -	0.4580	0.35 %	98.1
REL. # FUEL/BHPHR.	- ── ─	5.7130		91.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.97

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

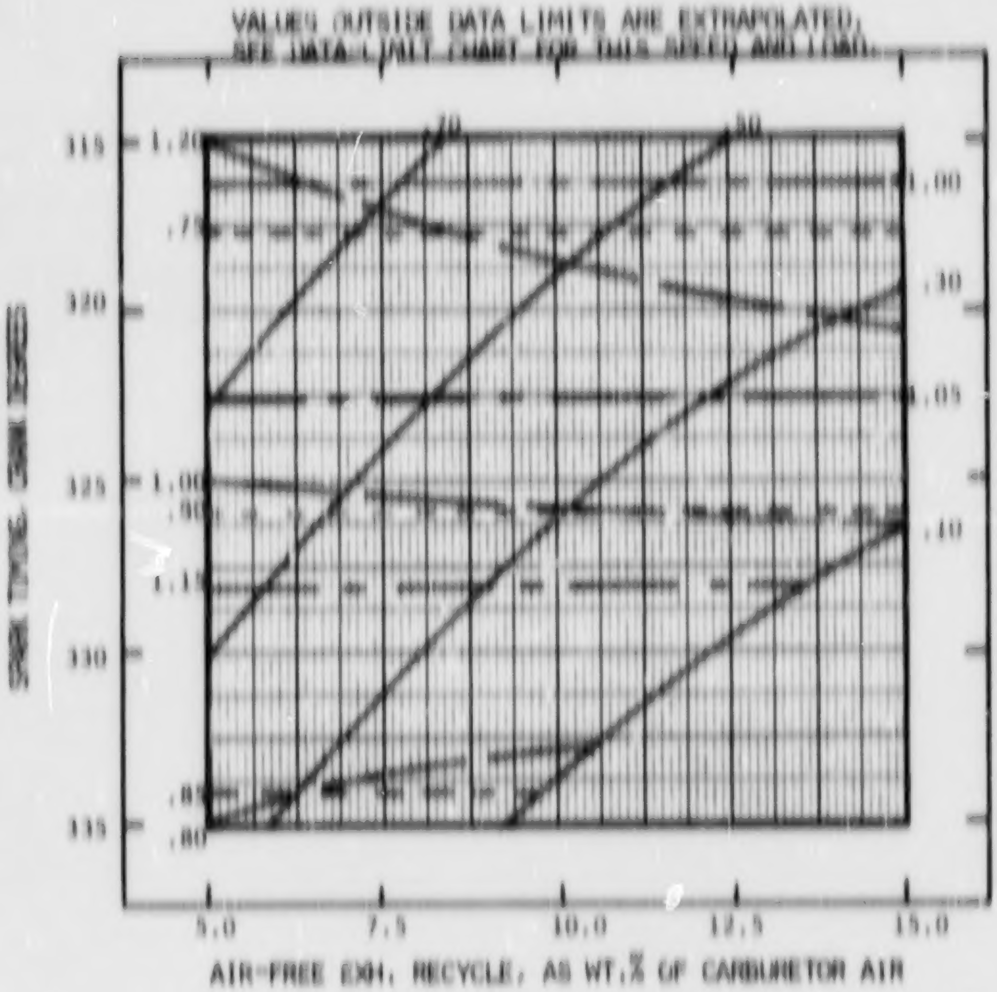
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 1500

CID 289 LB.-FT. TORQUE(1) 50

CONTROL SYSTEM A-1 A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———————	0.3963	1819 PPM NO	98.8
REL. # HC/HR. (FID)	– – – –	0.3793	967 PPM C6	97.3
REL. # CO/HR.	········	0.6580	0.35 %	98.1
REL. # FUEL/BHPHR.	– — –	0.7130		91.7

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.93

USPHS EXHAUST-RECYCLE PROGRAM
DATA LIMIT CHART

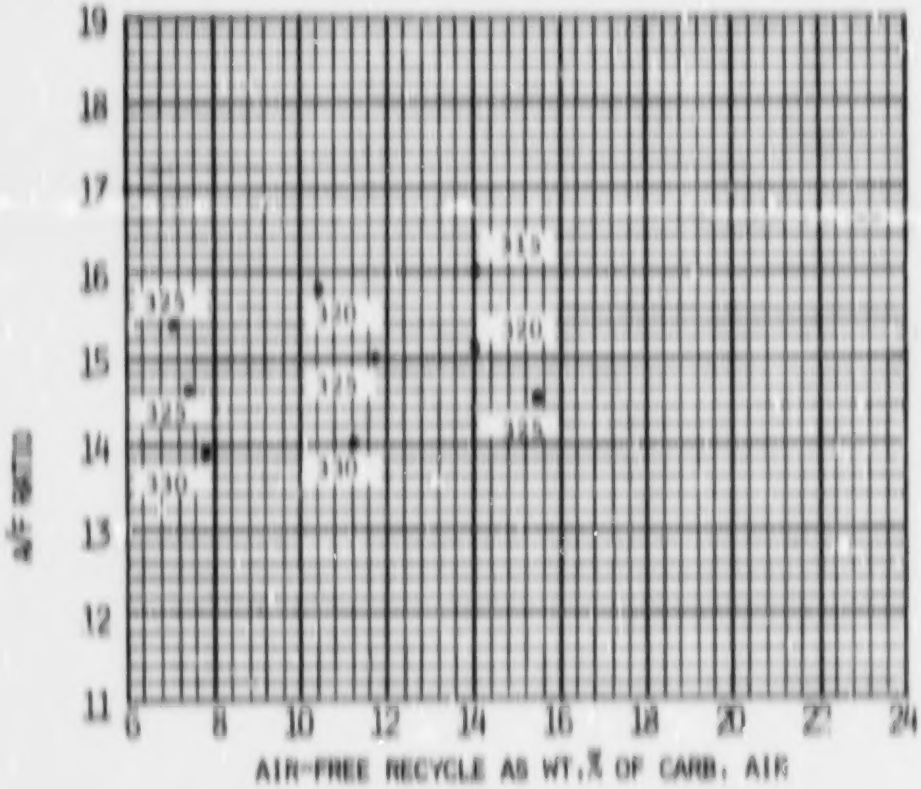
ENGINE: Ford RPM: 1500 LB.-FT. TQ. 100

MFR'S A/F: 15.0 MFR'S. SPARK: 116 IMAP(1) 18.2 "HG.

CARB. AIR RATE(1) 3.93 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 13.3-15.3
Spk. 116

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.9A

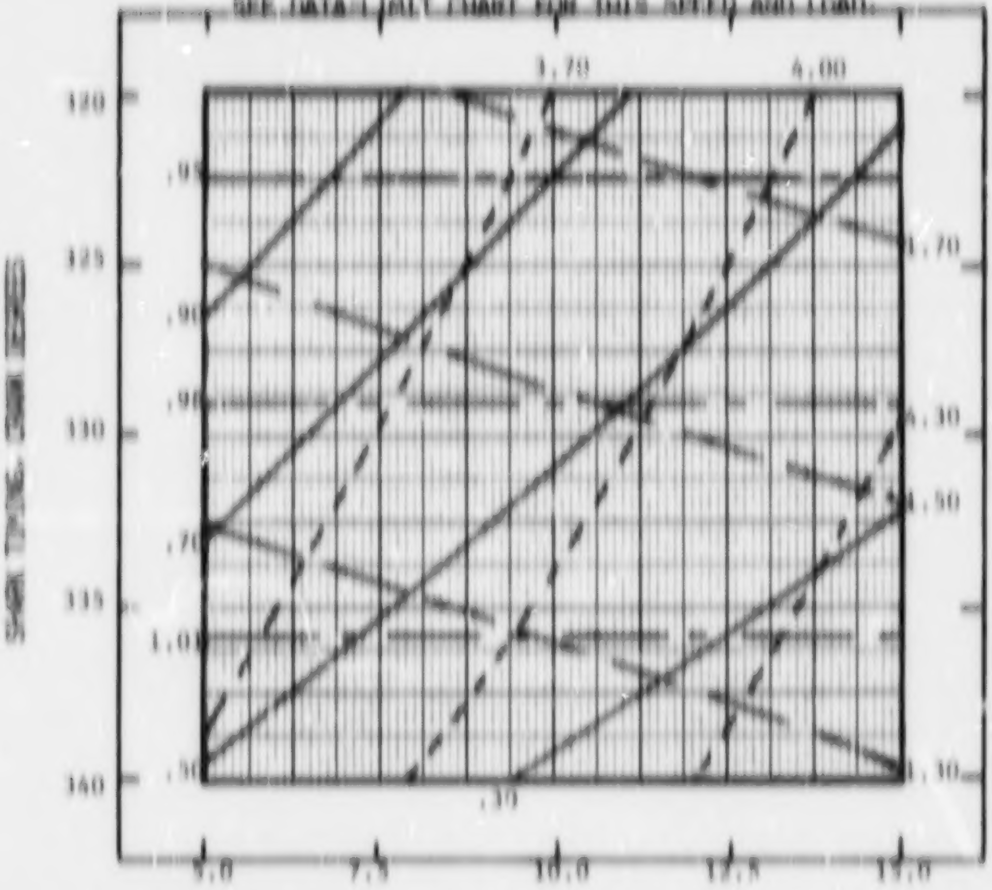
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 1500
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.8617	2582 PPM NO	98.1
REL. # C6HC/HR. (FID)	– – – –	0.5030	828 PPM C6	95.0
REL. # CO/HR.	-------	0.6047	0.30 %	97.6
REL. # FUEL/BHPHR.	– ▬ –	0.5477		92.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A3.95

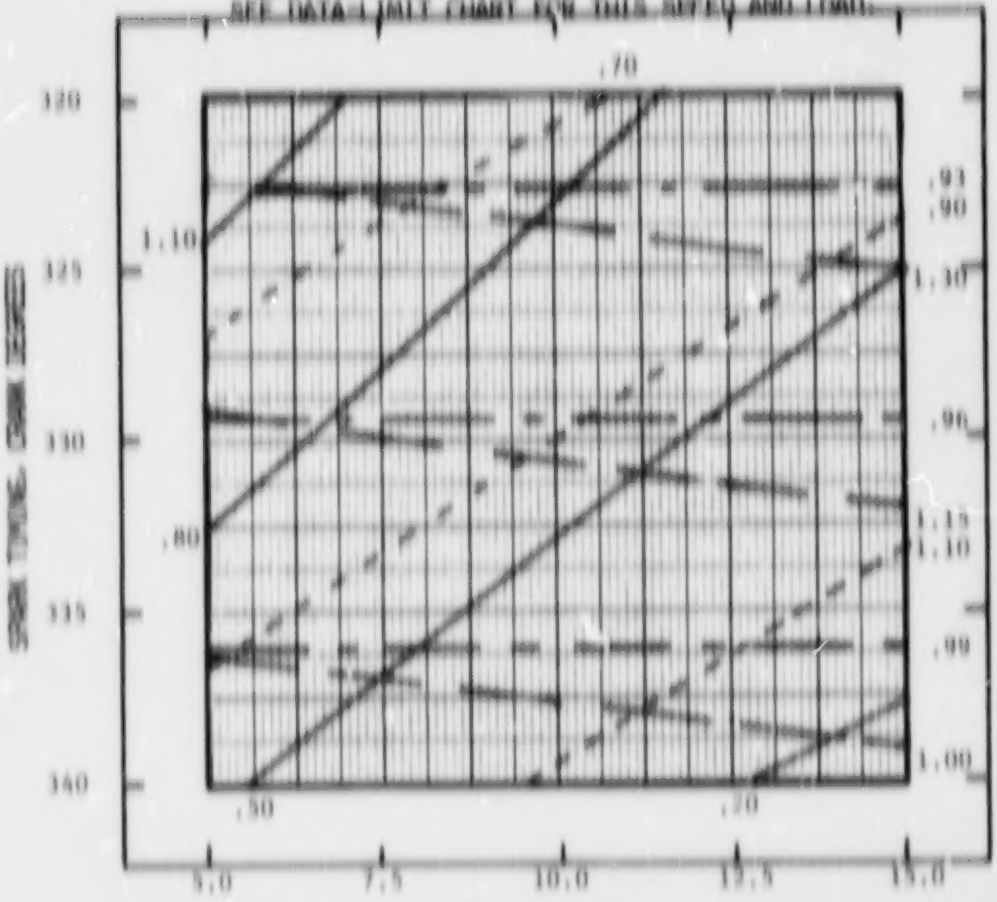
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Ford	ENGINE RPM	1500
CID	289	LB.-FT. TORQUE(1)	100
CONTROL SYSTEM	A-1	A/F RATIO(2)	15.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.8617	2582 PPM NO	98.1
REL. # C6HC/HR. (FID)	‒ ‒ ‒ ‒	0.5030	828 PPM C6	95.0
REL. # CO/HR.	┄┄┄┄	0.6042	0.30 %	97.6
REL. # FUEL/BHPHR.	‒ ▬ ‒	0.5477		92.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFE'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

DATA FOR FORD

[illegible]

FIGURE A2.9A

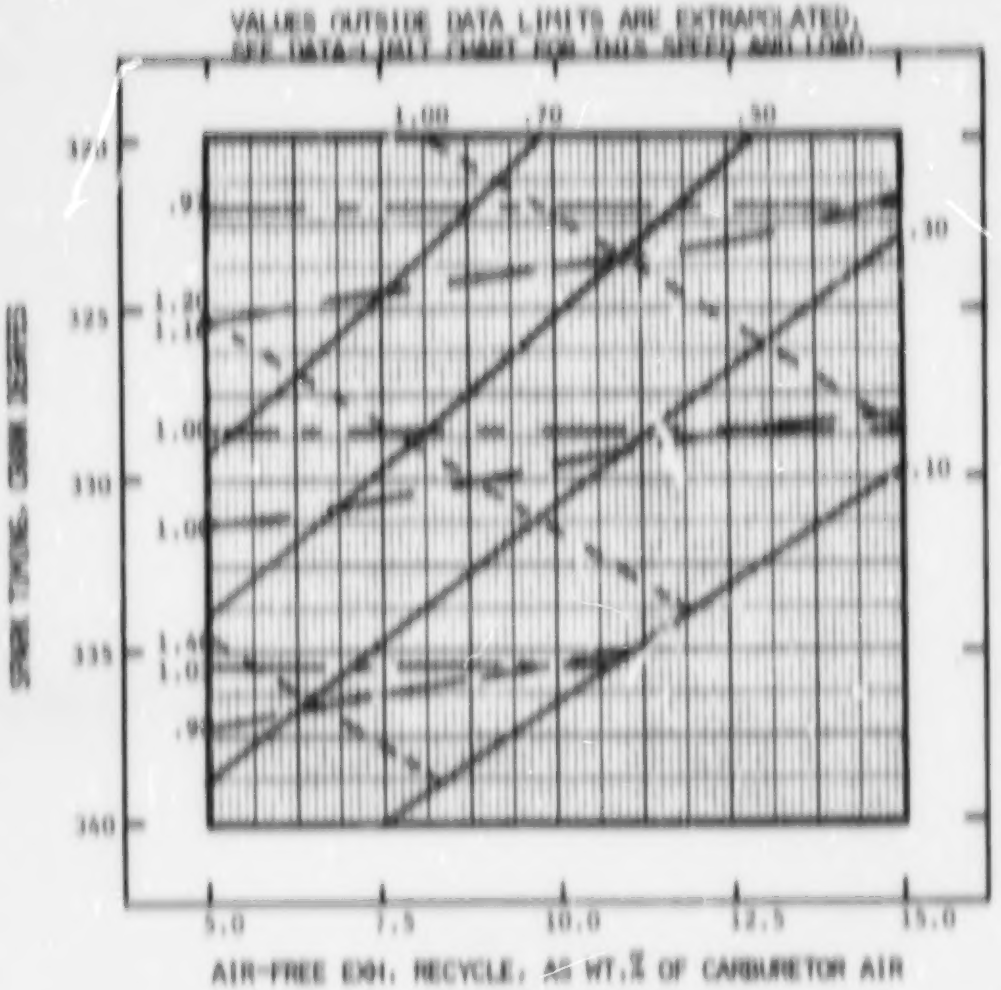
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford	ENGINE RPM 1300
CID 289	LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1	A/F RATIO(2) 16.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.8617	2582 PPM NO	98.1
REL. # C6HC/HR. (FID)	— — — —	0.5030	828 PPM C6	95.0
REL. # CO/HR.	--------	0.6047	0.30 %	97.6
REL. # FUEL/BHPHR.	— —— —	0.5477		92.2

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A-1.97

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

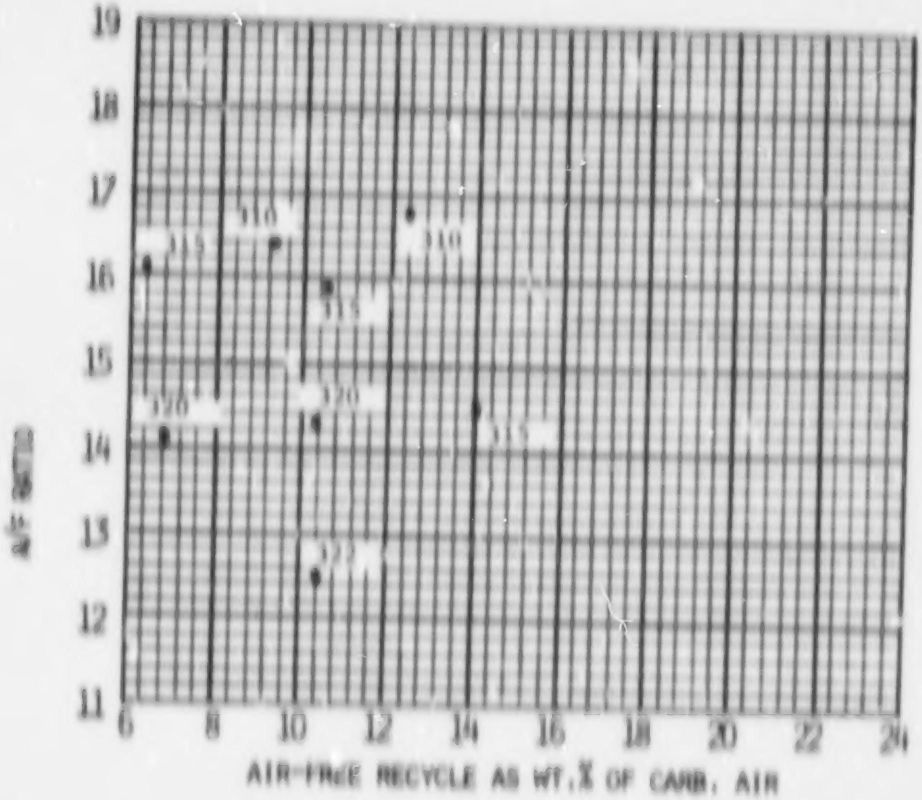
ENGINE: Ford RPM: 2000 LB.-FT. TQ. 50

MFR'S A/F: 15.6 MFR'S. SPARK: 322 IMAP(1) 12.8 "HG.

CARB. AIR RATE(1) 3.52 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.1-16.0
Spk. 321-342

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.98

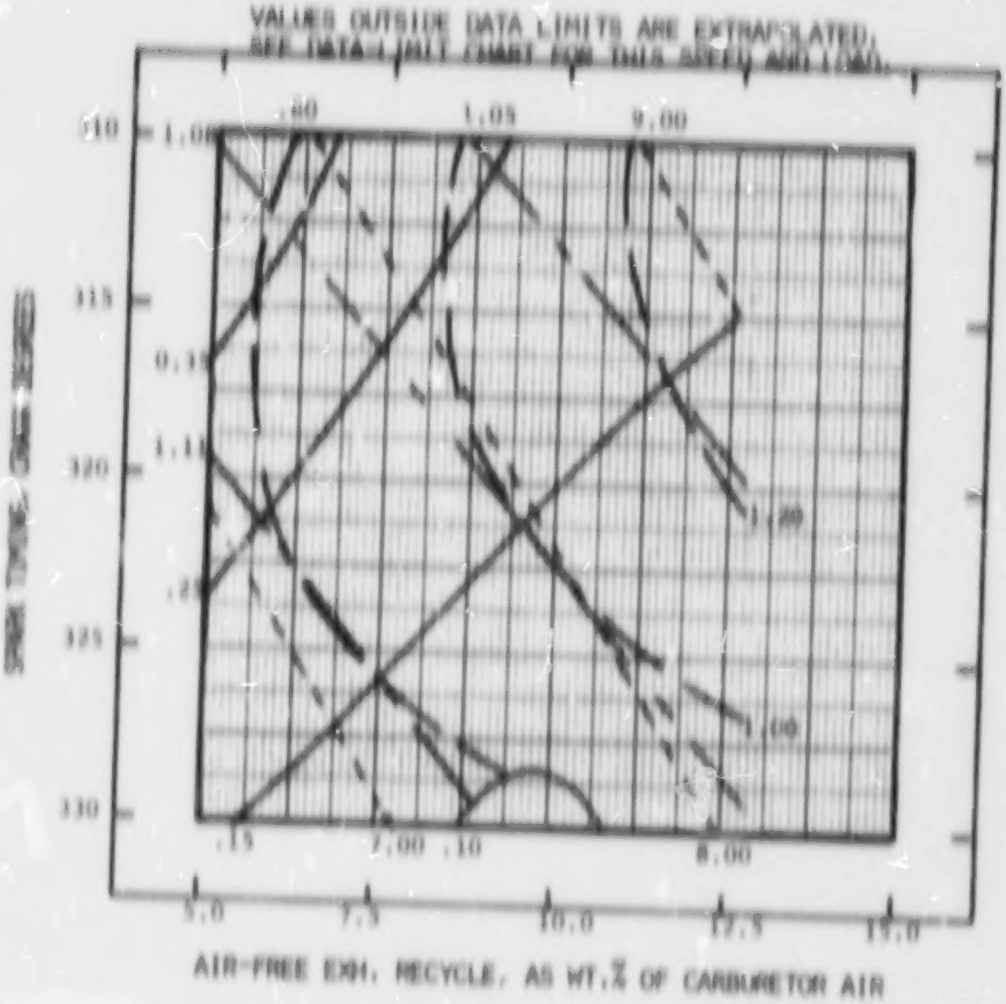
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Ford	ENGINE RPM	2000
CID	289	LB.-FT. TORQUE(1)	50
CONTROL SYSTEM	A-1	A/F RATIO(2)	12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	——— —	0.3688	1905 PPM NO	93.3
REL. # C6HC/HR. (FID)	— — — —	0.6136	788 PPM C6	97.5
REL. # CO/HR.	-------	0.6260	0.36 %	96.8
REL. # FUEL/BHPHR.	— —— —	0.7100		81.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

221

FIGURE A2.99

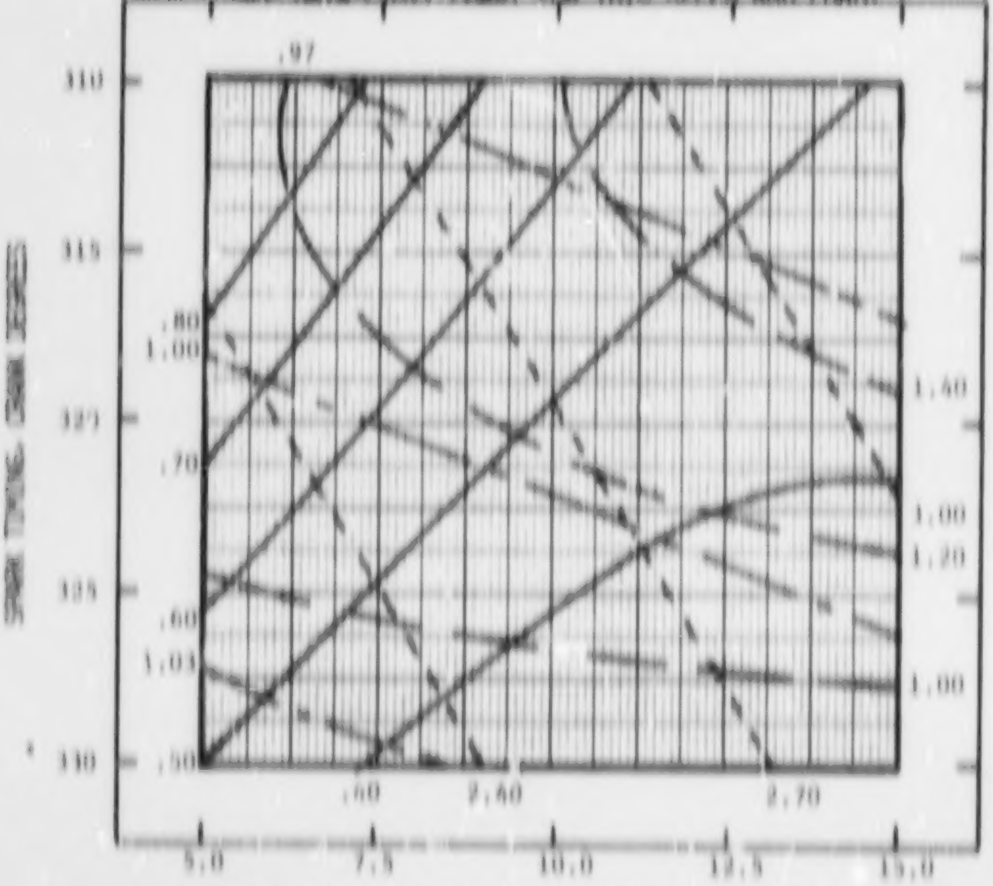
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.5488	1905 PPM NO	93.5
REL. # C6HC/HR. (FID)	— — — —	0.5130	788 PPM C6	97.3
REL. # CO/HR.	-------	0.6260	0.36 %	96.6
REL. # FUEL/BHPHR.	-- — --	0.7100		81.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A2.100

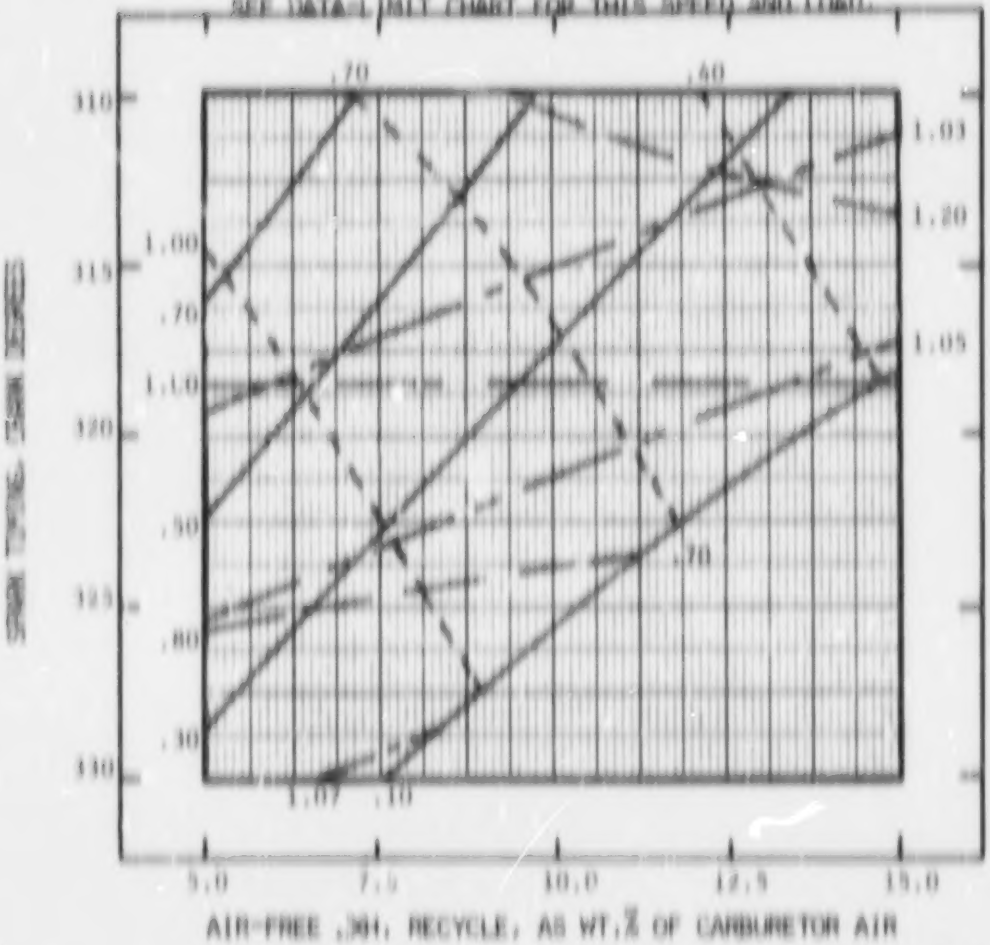
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.5688	1905 PPM NO	93.5
REL. # C6HC/HR. (FID)	– – – –	0.6130	788 PPM C6	97.5
REL. # CO/HR.	········	0.6260	0.36 %	96.6
REL. # FUEL/BHPHR.	– — –	0.7100		81.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.101

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

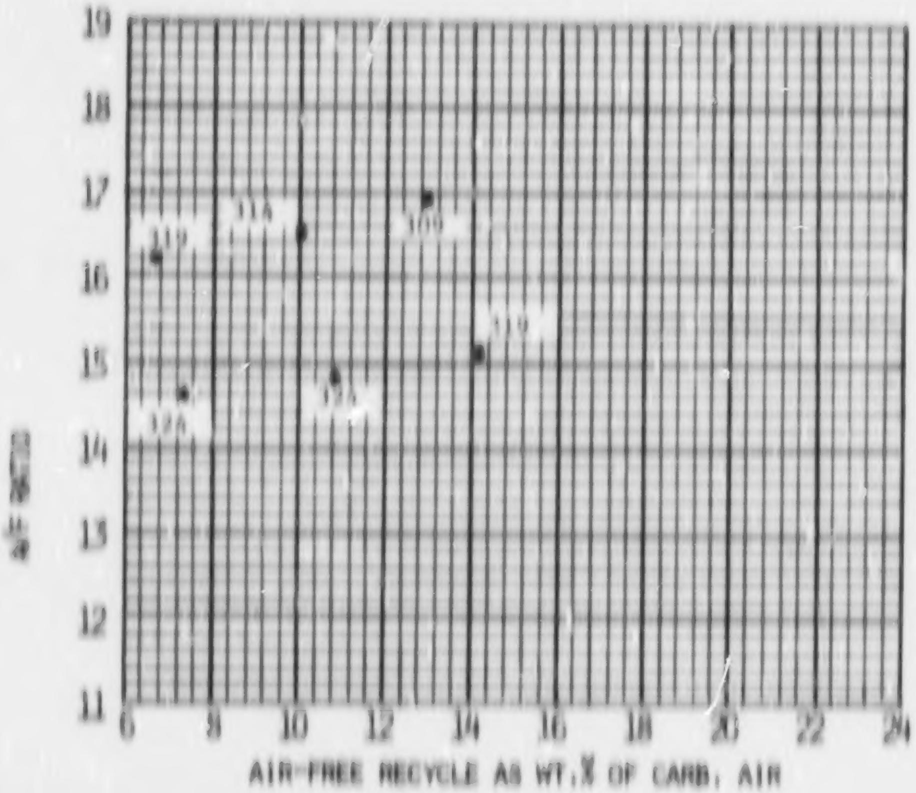
ENGINE: Ford RPM: 2000 LB.-FT. TQ. 75

MFR'S A/F: 15.6 MFR'S. SPARK: 124 IMAP(1) 15.6 "HG.

CARB. AIR RATE(1) 4.47 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 14.1-15.6
Spk. 124

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.102

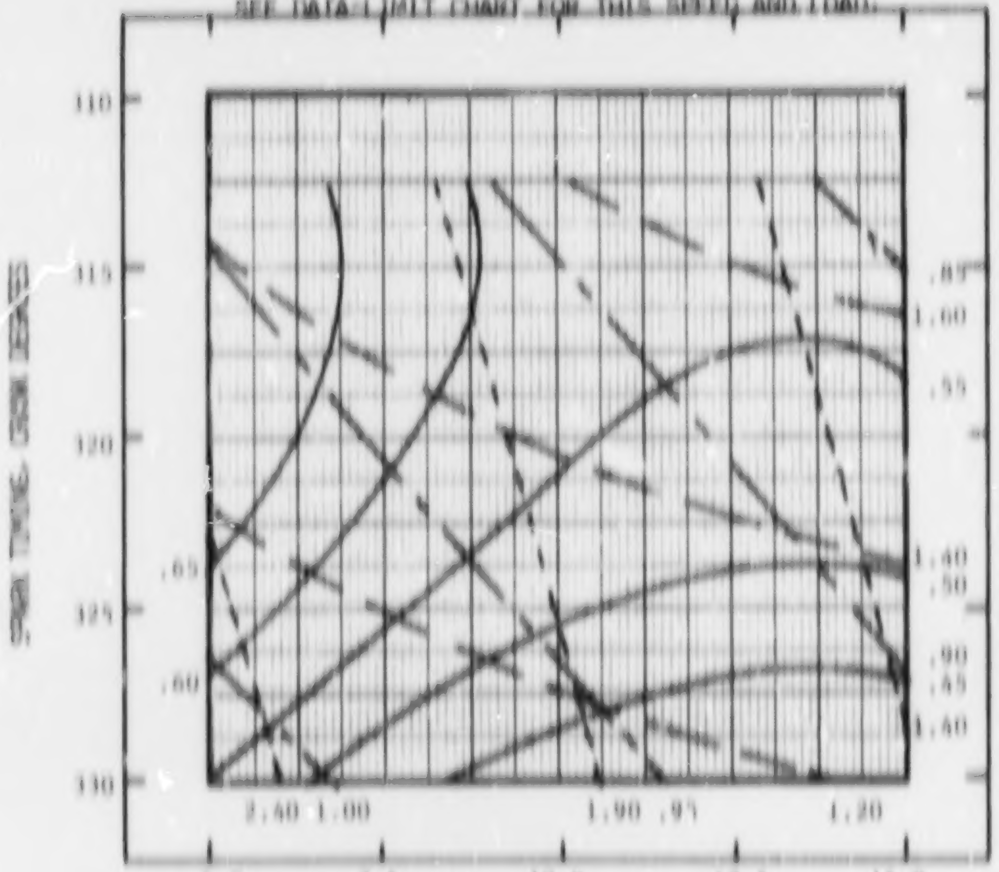
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED; SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.3427	3666 PPM NO	99.7
REL. # C6HC/HR. (FID)	= = = =	0.6097	700 PPM C6	98.6
REL. # CO/HR.	-------	0.7265	0.36 %	97.2
REL. # FUEL/BHPHR.	- — -	0.6059		93.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle air)/Fuel

(3) MEAN VALUE AT MFR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.103

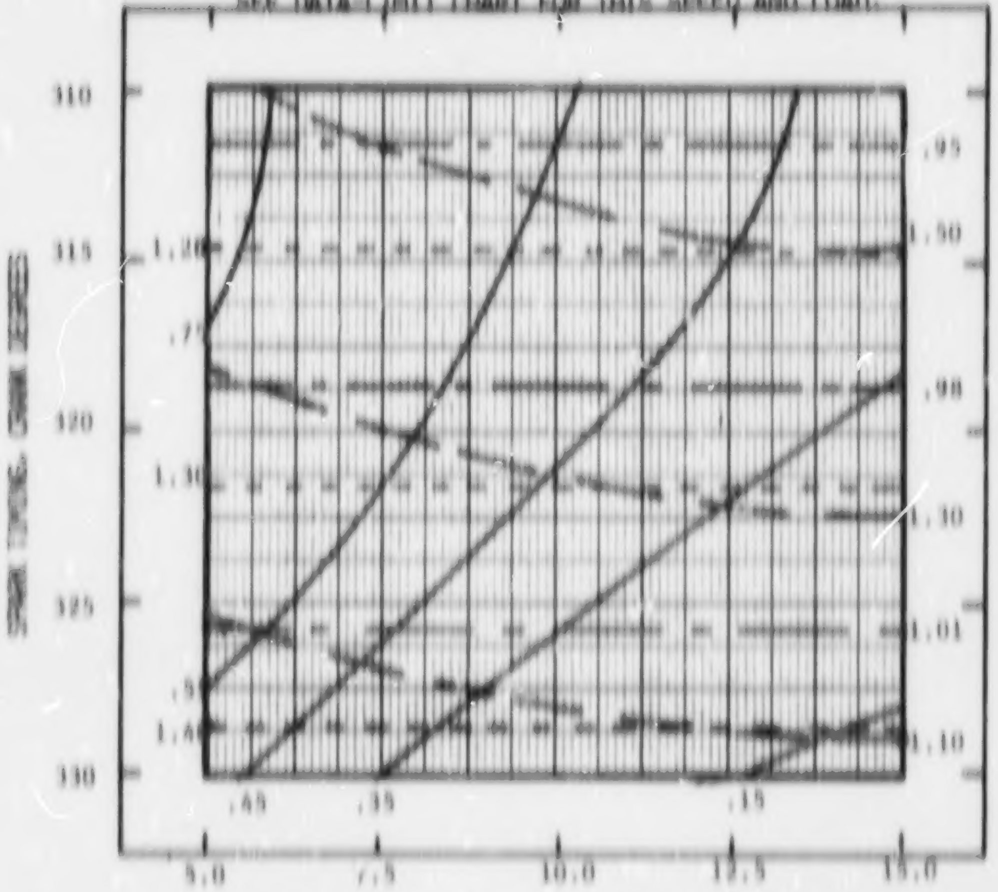
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 2000
CID 289
LB.-FT. TORQUE(1) 75
CONTROL SYSTEM A-1
A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3627	3664 PPM NO	99.7
REL. # C6HC/HR. (FID)	- - - -	0.5657	700 PPM C6	98.6
REL. # CO/HR.	-------	0.7255	0.34 %	97.2
REL. # FUEL/BHPHR.	- — -	0.6059		91.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.104

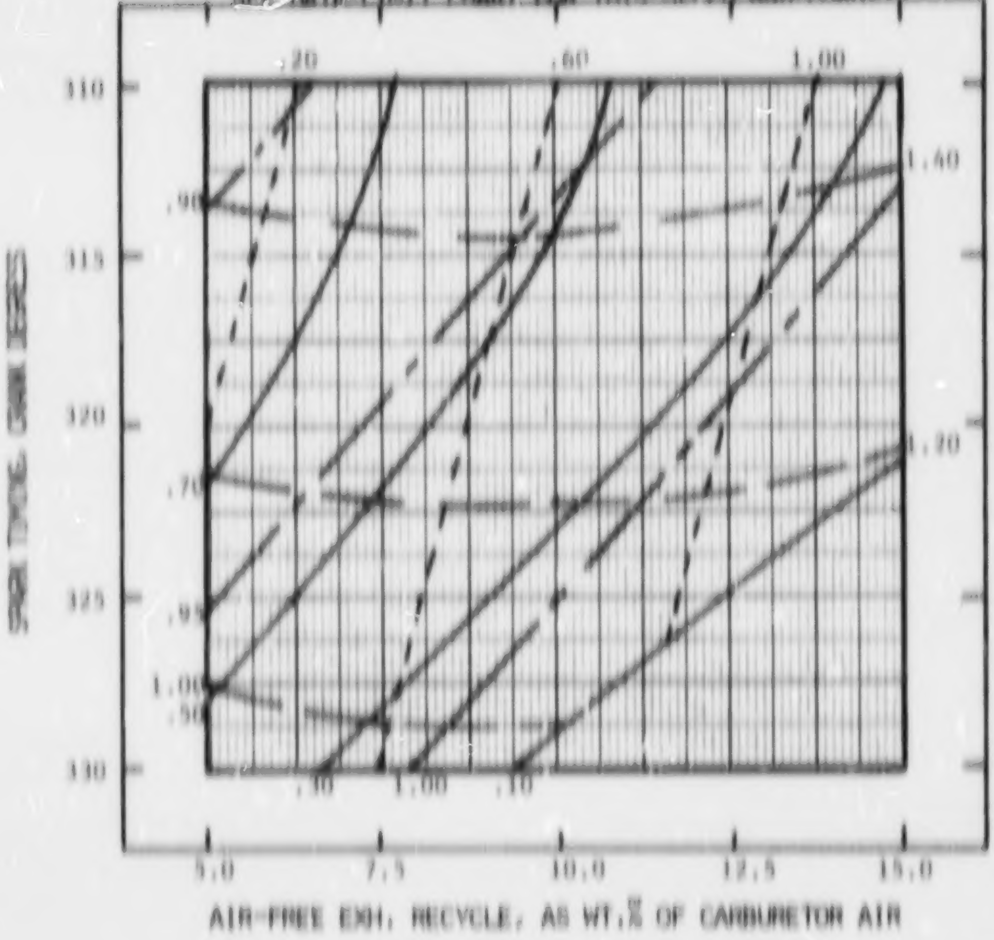
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 2000
CID 289
LB.-FT. TORQUE(1) 75
CONTROL SYSTEM A-1
A/F RATIO(2) 16.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	═══	1.3627	1644 PPM NO	99.7
REL. # C6HC/HR. (FID)	= = = =	0.6697	700 PPM C6	98.5
REL. # CO/HR.	------	0.7265	0.35 %	97.2
REL. # FUEL/BHPHR.	= — =	0.6059		93.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.105

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

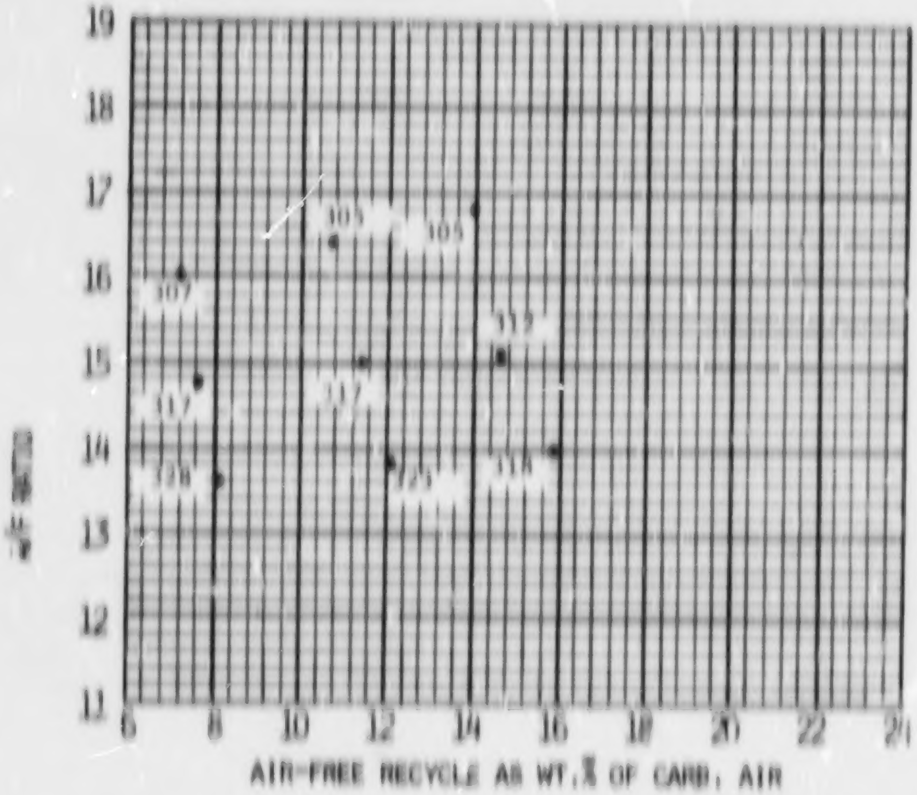
ENGINE: Ford RPM: 2000 LB.-FT. TQ. 100

MFR'S A/F: 15.5 MFR'S. SPARK: 127 IMAP(1) 17.8 "HG.

CARB. AIR RATE(1) 5.32 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 13.2-15.5
Spk. 127-128

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.106

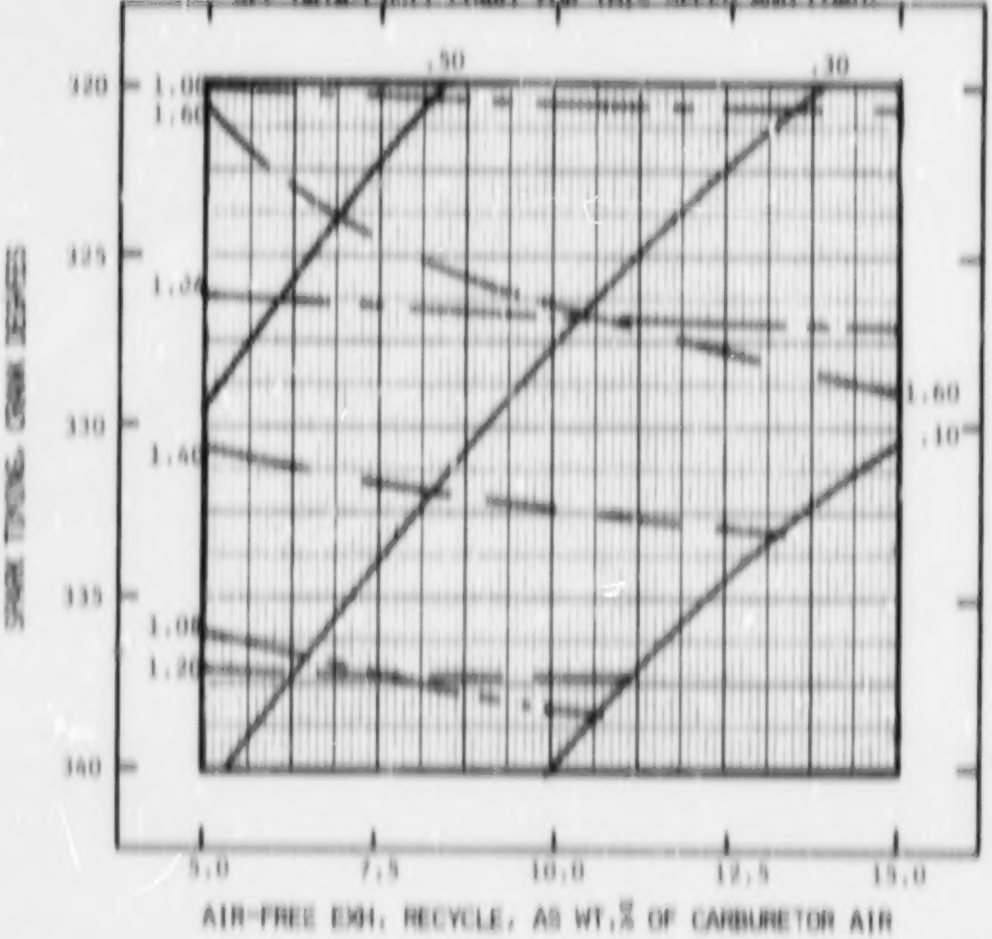
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 13.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



CO = 7.11 x Base
for all of th
map

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.1680	2640 PPM NO	95.5
REL. # C6HC/HR. (FID)	- - - -	0.5698	582 PPM C6	91.2
REL. # CO/HR.	--------	0.7912	0.29 %	98.0
REL. # FUEL/BHPHR.	- — -	0.3466		88.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.107

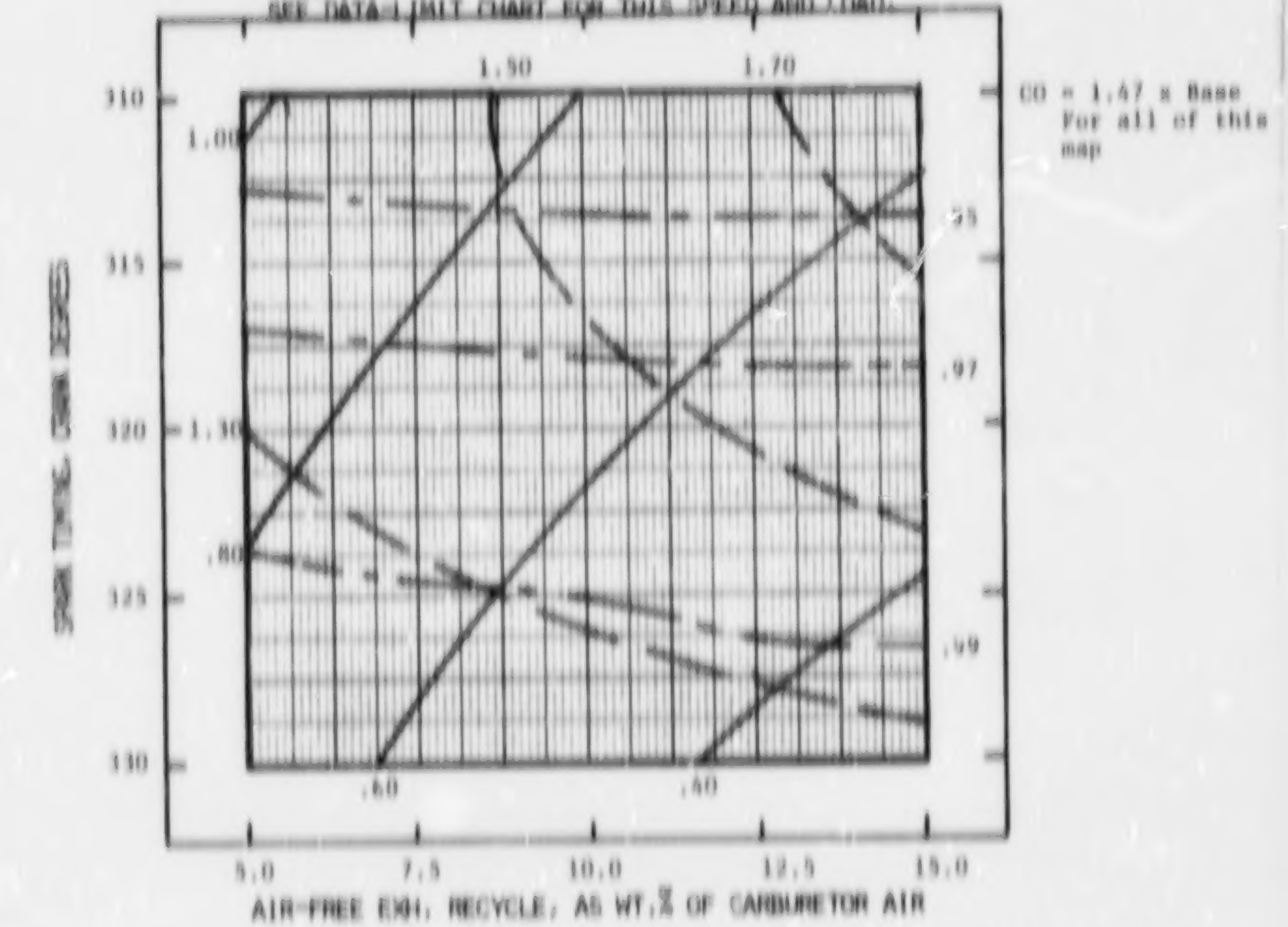
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 15.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	1.1688	2640 PPM NO	95.5
REL. # C6HC/HR. (FID)	– – – –	0.4698	582 PPM C6	91.2
REL. # CO/HR.	┅┅┅┅	0.7912	0.29 %	98.0
REL. # FUEL/BHPHR.	– — –	0.5465		88.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

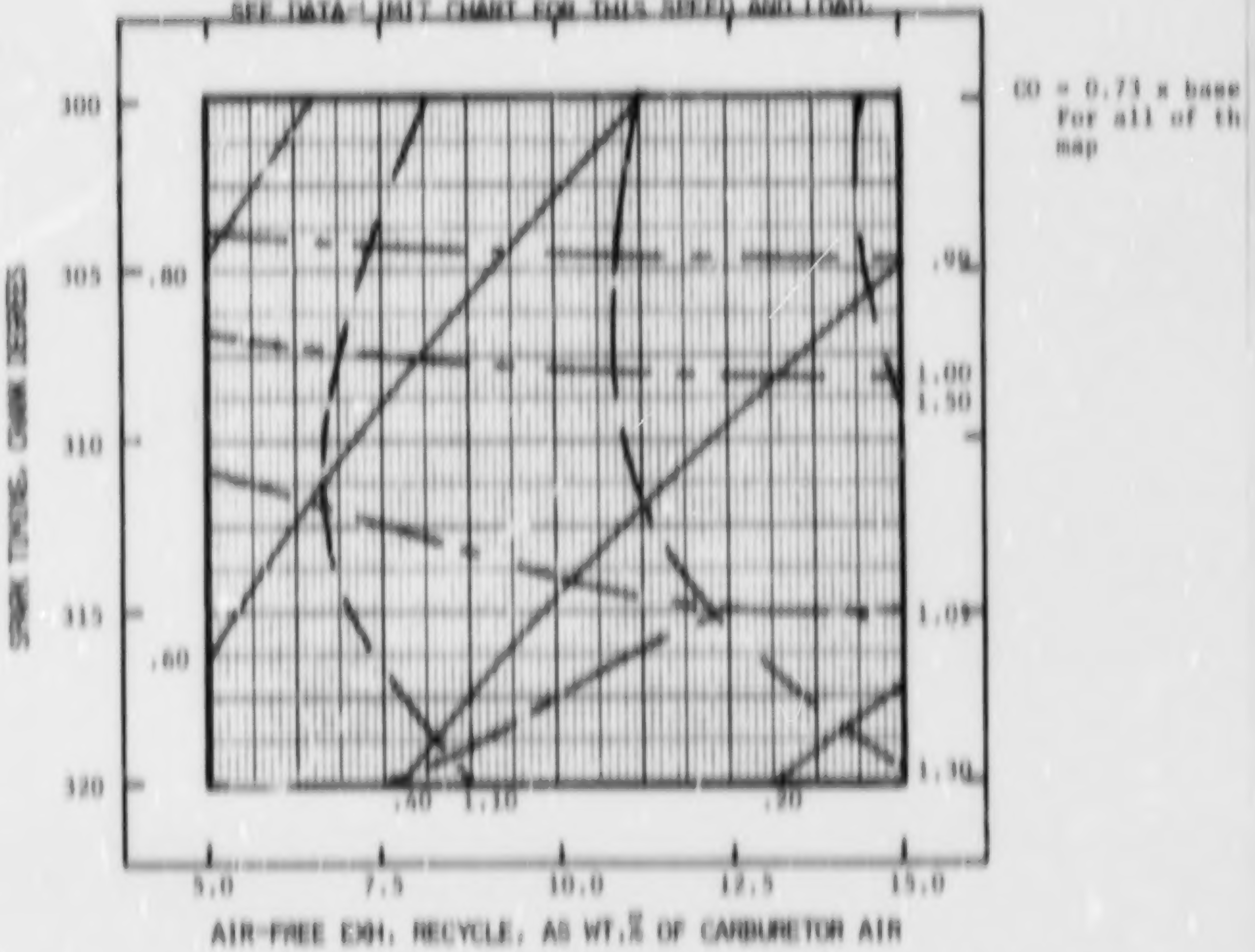
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.108

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2000
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 16.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.1688	2640 PPM NO	95.5
REL. # C_6HC/HR. (FID)	- - - -	0.5698	382 PPM C_6	91.2
REL. # CO/HR.	········	0.7912	0.29 %	98.0
REL. # FUEL/BHPHR.	- — -	0.5466		88.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.109

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

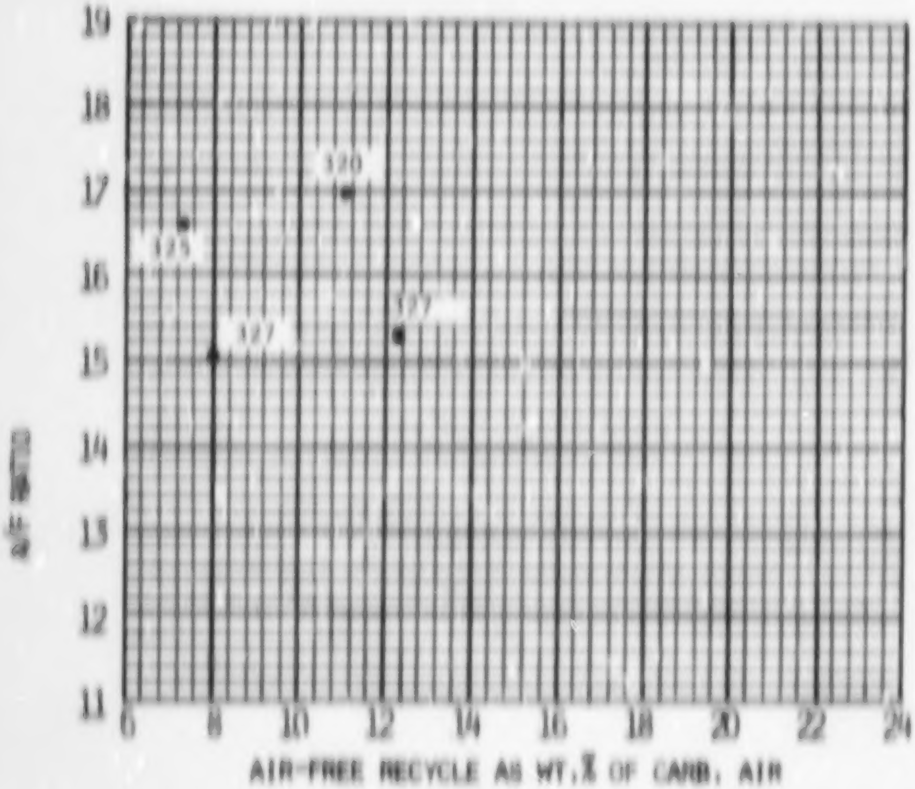
ENGINE: Ford RPM: 200 LB.-FT. TQ. 142

MFR'S A/F: 16.0 MFR'S. SPARK: 337 IMAP(1) 21.6 "HG.

CARB. AIR RATE(1) 7.11 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 15.6-16.0
Spk. 337

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.110

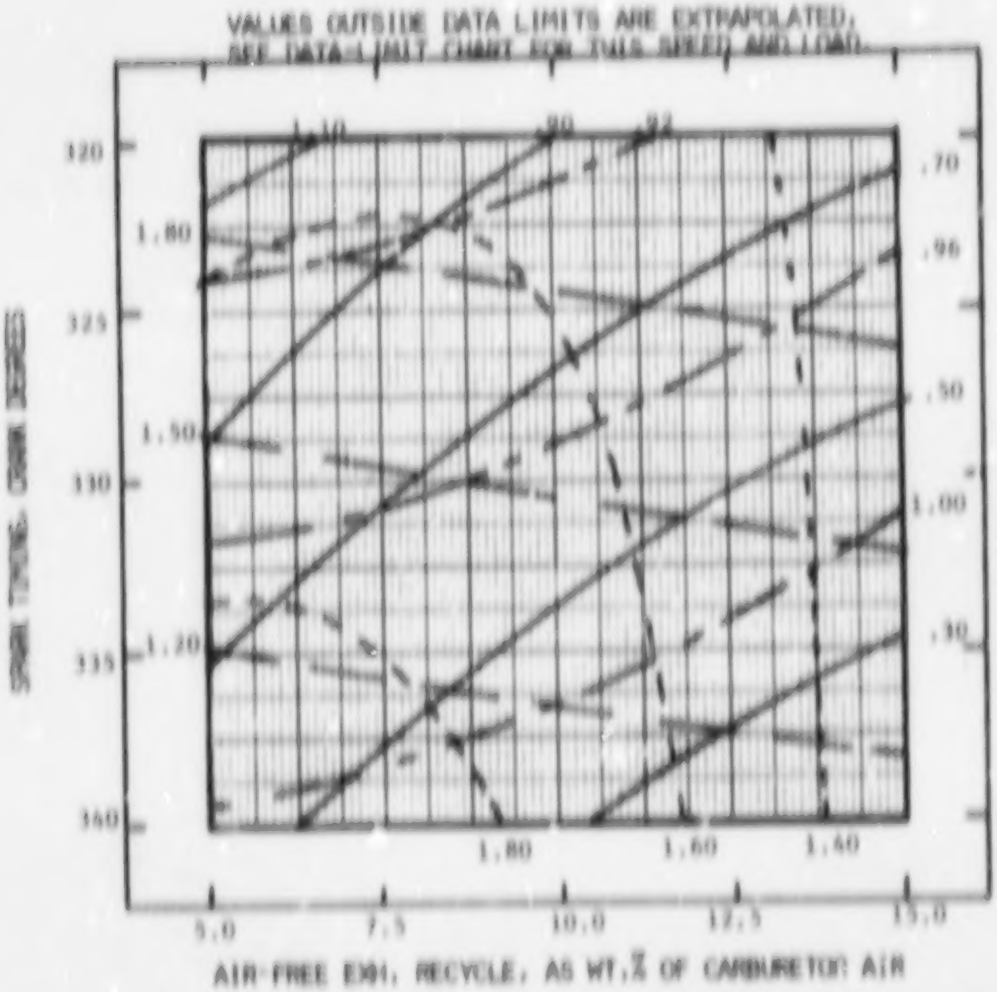
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 2000
CID 289
LB.-FT. TORQUE(1) 140
CONTROL SYSTEM A-1
A/F RATIO(2) 15.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.9905	3441 PPM NO	97.6
REL. # C6/HC/HR. (FID)	‒ ‒ ‒ ‒	0.4380	470 PPM C6	99.2
REL. # CO/HR.	-------	1.2750	0.36 %	99.2
REL. # FUEL/BHPHR.	‒ ▬ ‒	0.5056		91.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel
(3) MEAN VALUE AT RPR'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.111

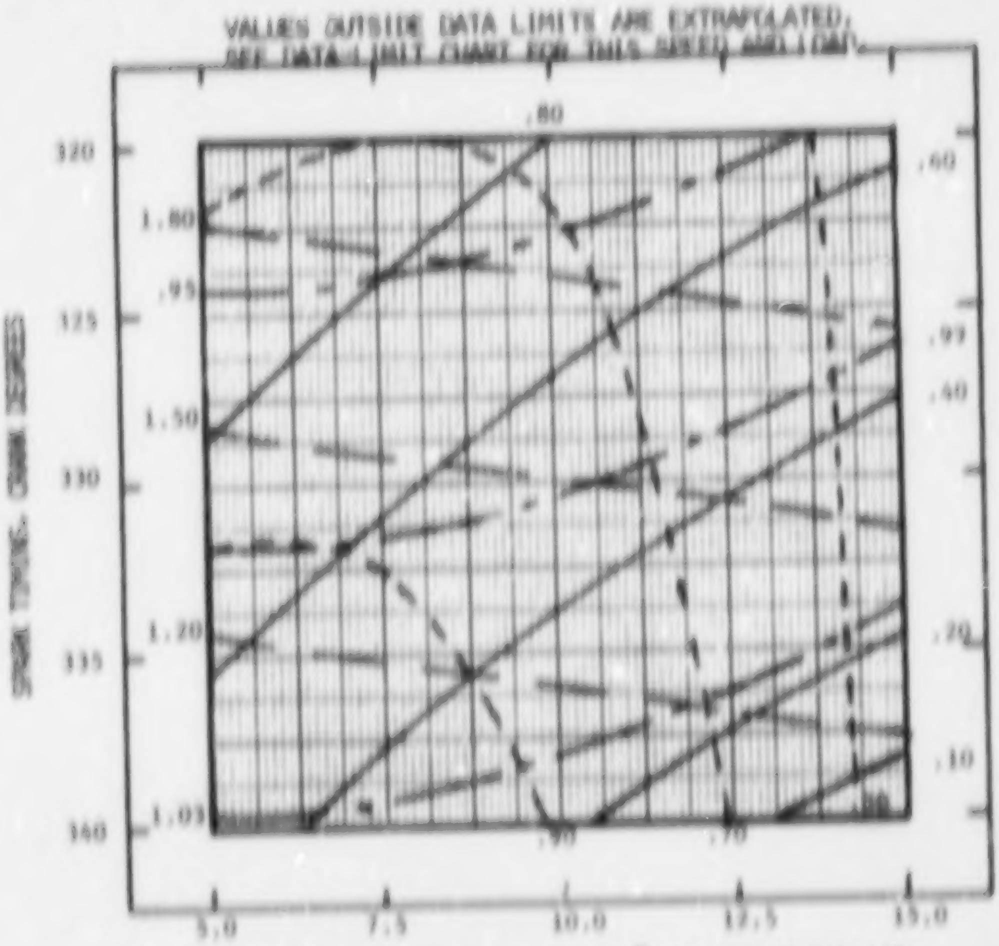
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 2000
CID 289
LB.-FT. TORQUE(1) 160
CONTROL SYSTEM A-1
A/F RATIO(2) 15.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.9905	3663 PPM NO	97.6
REL. # C6HC/HR. (FID)	– – – –	0.6380	520 PPM C6	99.2
REL. # CO/HR.	········	1.2750	0.36 %	99.2
REL. # FUEL/BHPHR.	– — –	0.5056		91.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

[illegible]

FIGURE A2.112

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

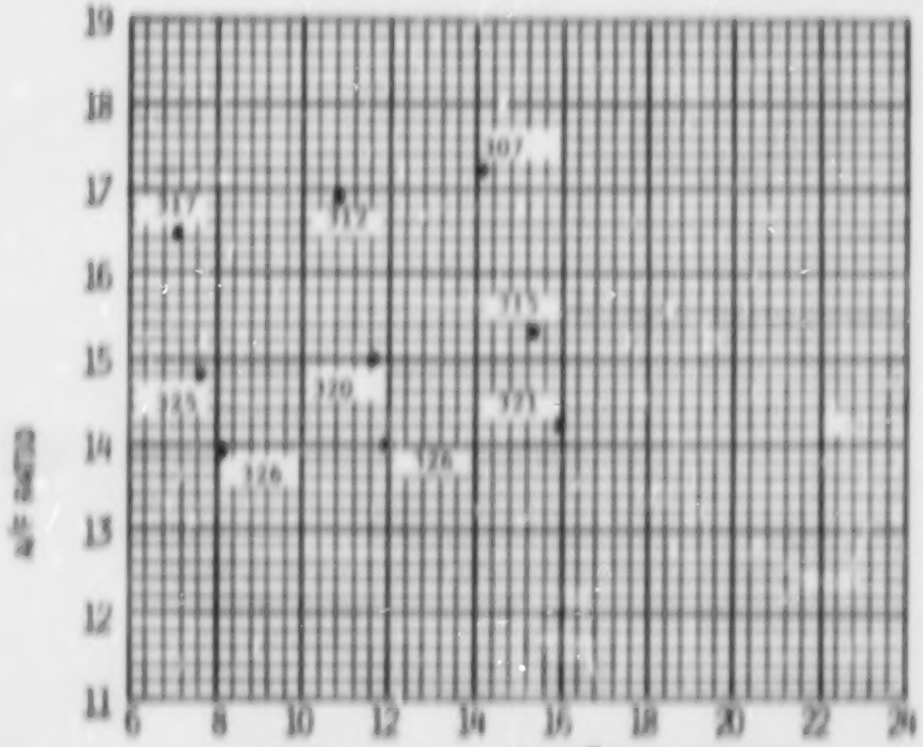
ENGINE: Ford RPM: 2500 LB.-FT. TQ. 100

MFR'S A/F: 15.7 MFR'S. SPARK: 127 IMAP(1) 19.1 "HG.

CARB. AIR RATE(1) 6.96 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 13.5-15.9
Spk. 126-127

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.113

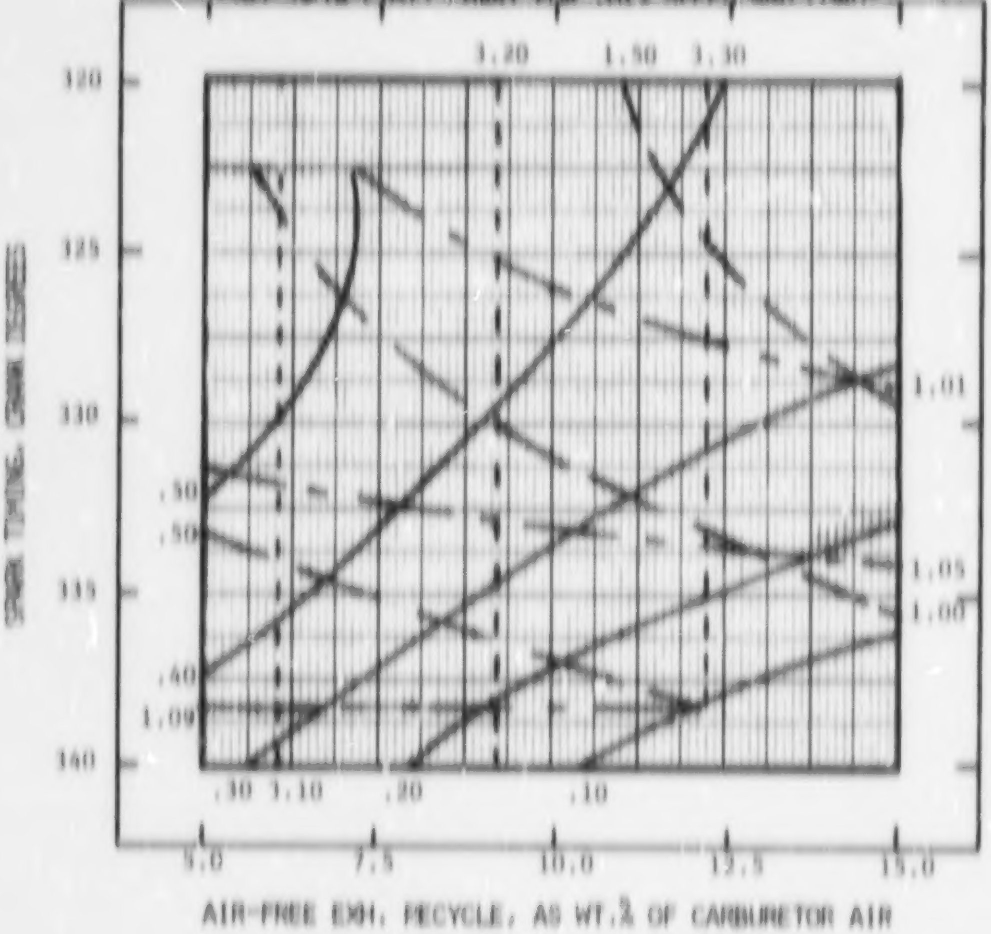
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2500
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 14.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO_2/HR.	———	2.0402	1151 PPM NO	99.3
REL. # C_6HC/HR. (FID)	– – – –	0.1507	319 PPM C_6	99.3
REL. # CO/HR.	········	1.3970	0.60 %	95.7
REL. # FUEL/BHPHR.	– — –	0.5559		85.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.11A

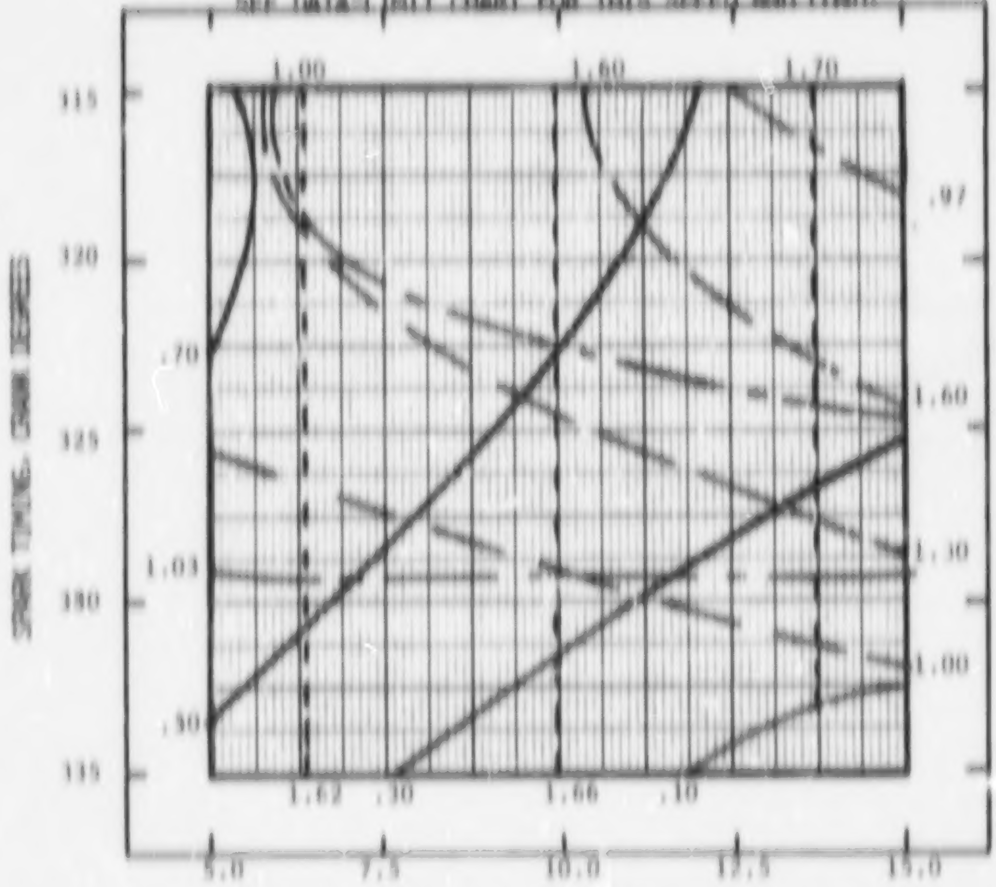
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford ENGINE RPM 2500
CID 289 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 15.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	2.0402	1551 PPM NO	99.3
REL. # C6/HC/HR. (FID)	− − − −	0.3597	119 PPM C6	99.3
REL. # CO/HR.	-------	1.3970	0.60 %	95.7
REL. # FUEL/BHPHR.	○ — ○	0.3559		85.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL.: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE 73.115

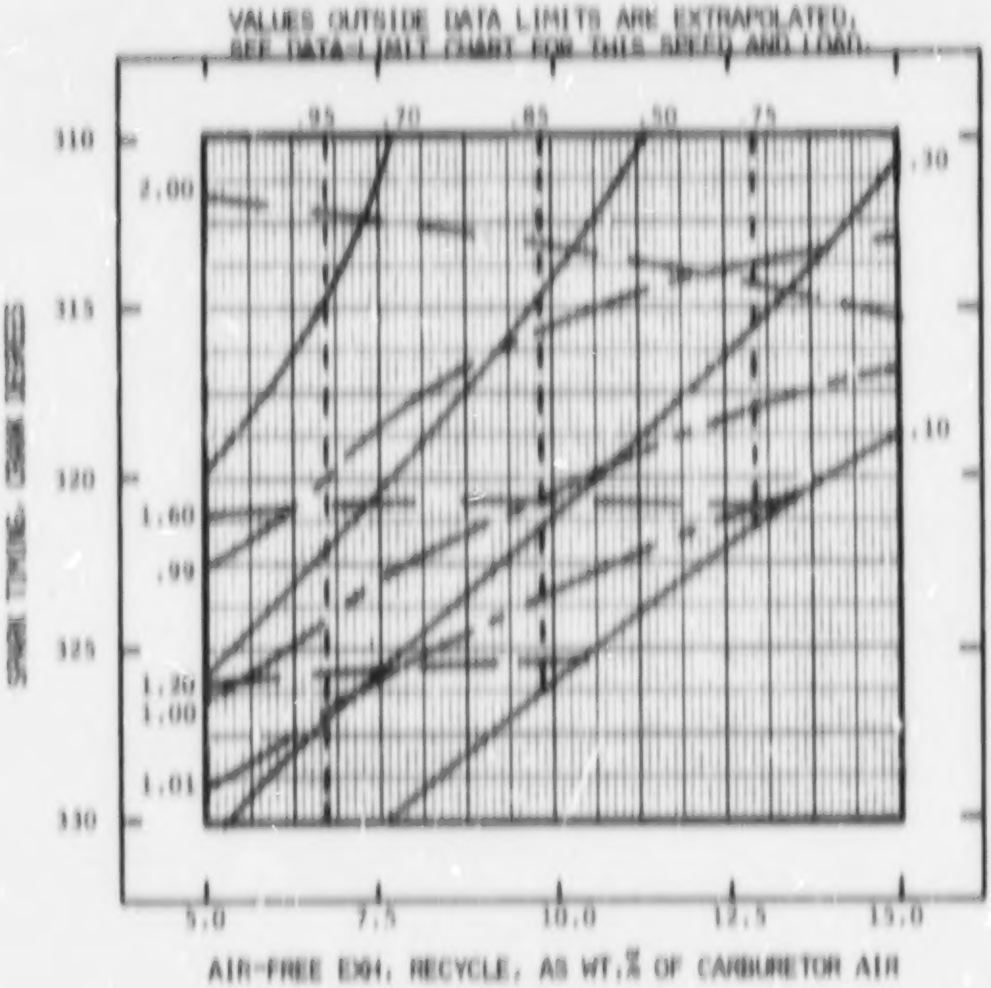
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Ford
ENGINE RPM 2500
CID 289
LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1
A/F RATIO(2) 17.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	2.0402	1551 PPM NO	99.1
REL. # C_6HC/HR. (FID)	- - - -	0.3597	119 PPM C_6	99.1
REL. # CO/HR.	········	1.3970	0.40 %	93.7
REL. # FUEL/BHPHR.	— — —	0.5559		85.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

DATA FOR CHEVROLET

FIGURE A7.116

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

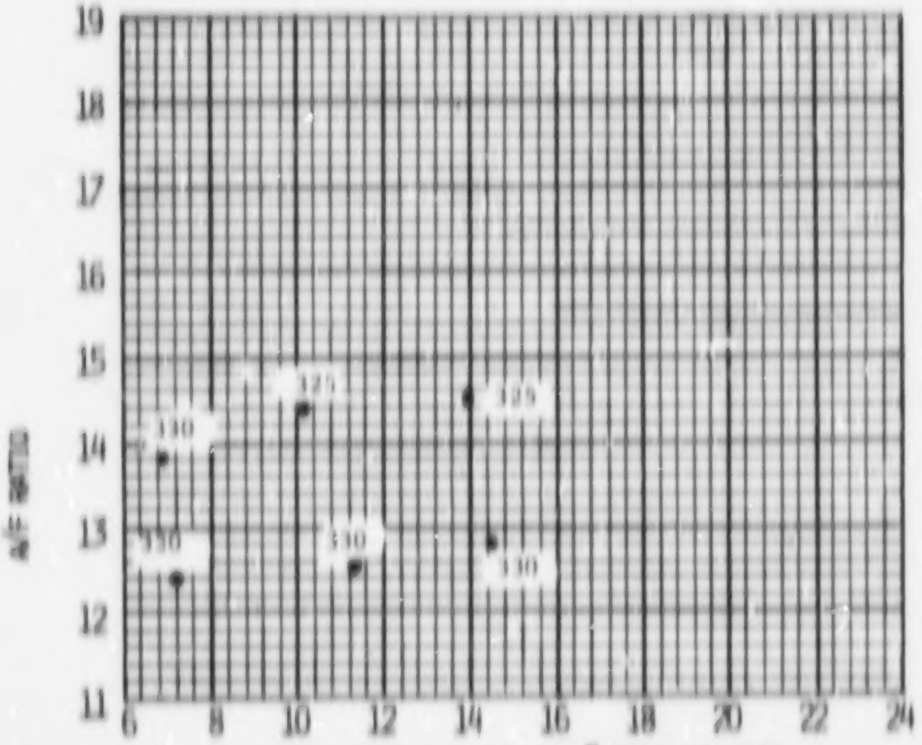
ENGINE: Chevrolet RPM: 1500 LB.-FT. TQ. 50

MFR'S A/F: 13.5/1 MFR'S. SPARK: 331 IMAP(1) 12.2 "HG.

CARB. AIR RATE(1) 2.44 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.0-13.6
Spk. 331

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.117

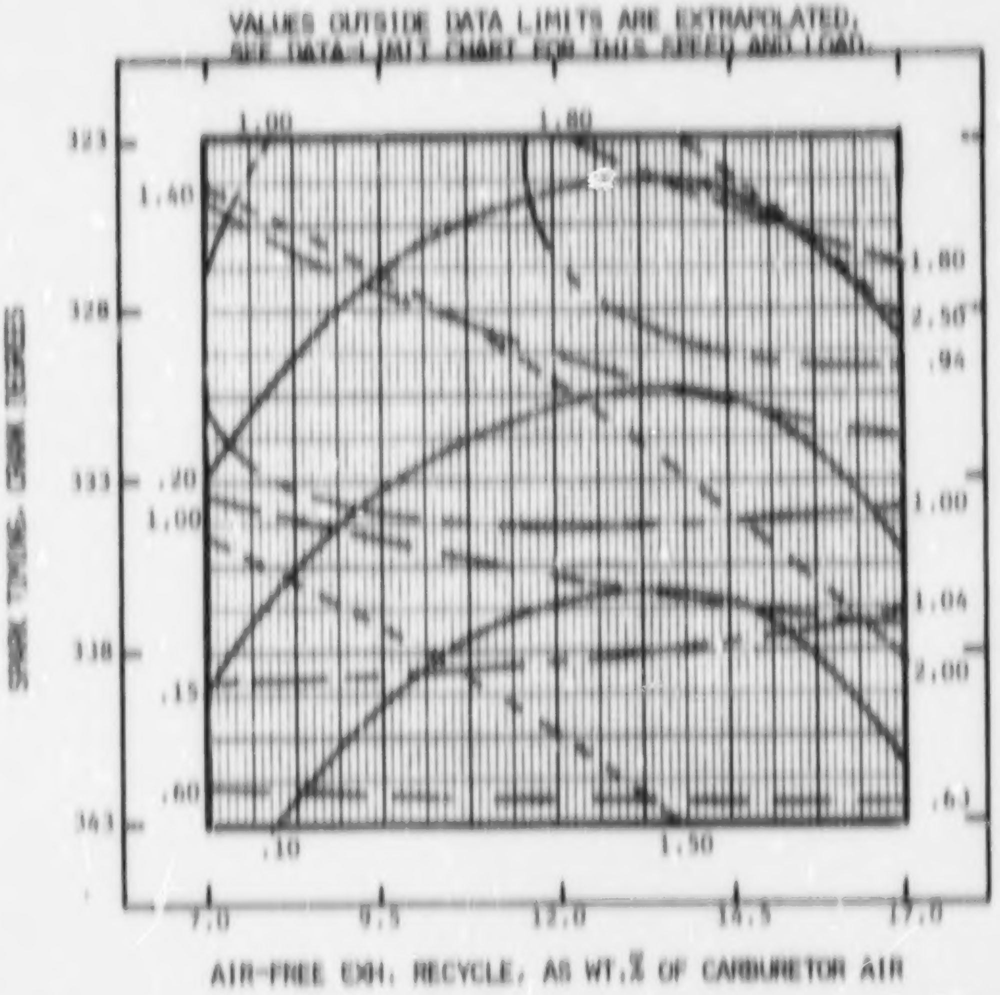
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN
REL. # NO2/HR.	▬▬▬	0.2708	1148 PPM NO	97.4
REL. # C6HC/HR. (FID)	‒ ‒ ‒ ‒	0.4481	1075 PPM C6	97.0
REL. # CO/HR.	--------	2.5750	1.67 %	98.4
REL. # FUEL/BHPHR.	‒ ‒‒ ‒	0.7534		97.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%. [illegible]

FIGURE A2.11P

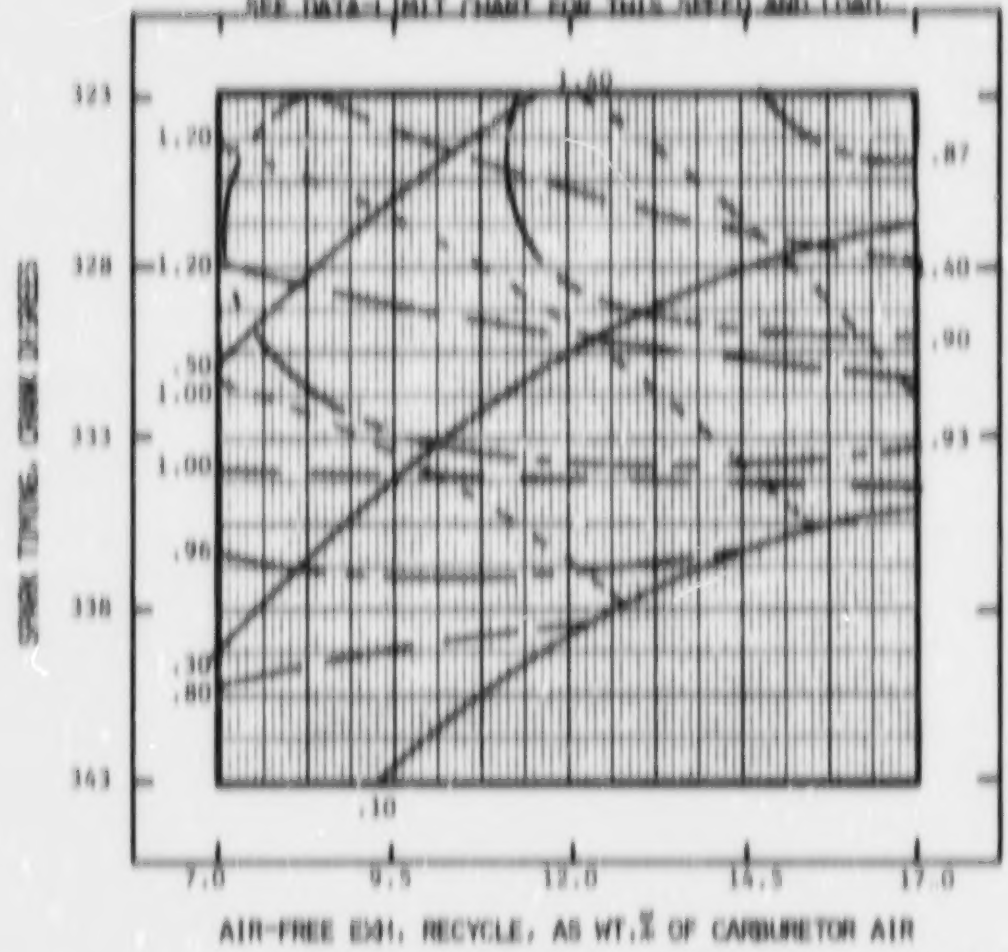
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 25
CONTROL SYSTEM A-1 A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.		% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.2708	1168	PPM NO	97.4
REL. # C6HC/HR. (FID)	– – – –	0.6681	1075	PPM C6	97.0
REL. # CO/HR.	------	2.5750	1.67	%	98.5
REL. # FUEL/BHPHR.	= == =	0.7525			97.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.119

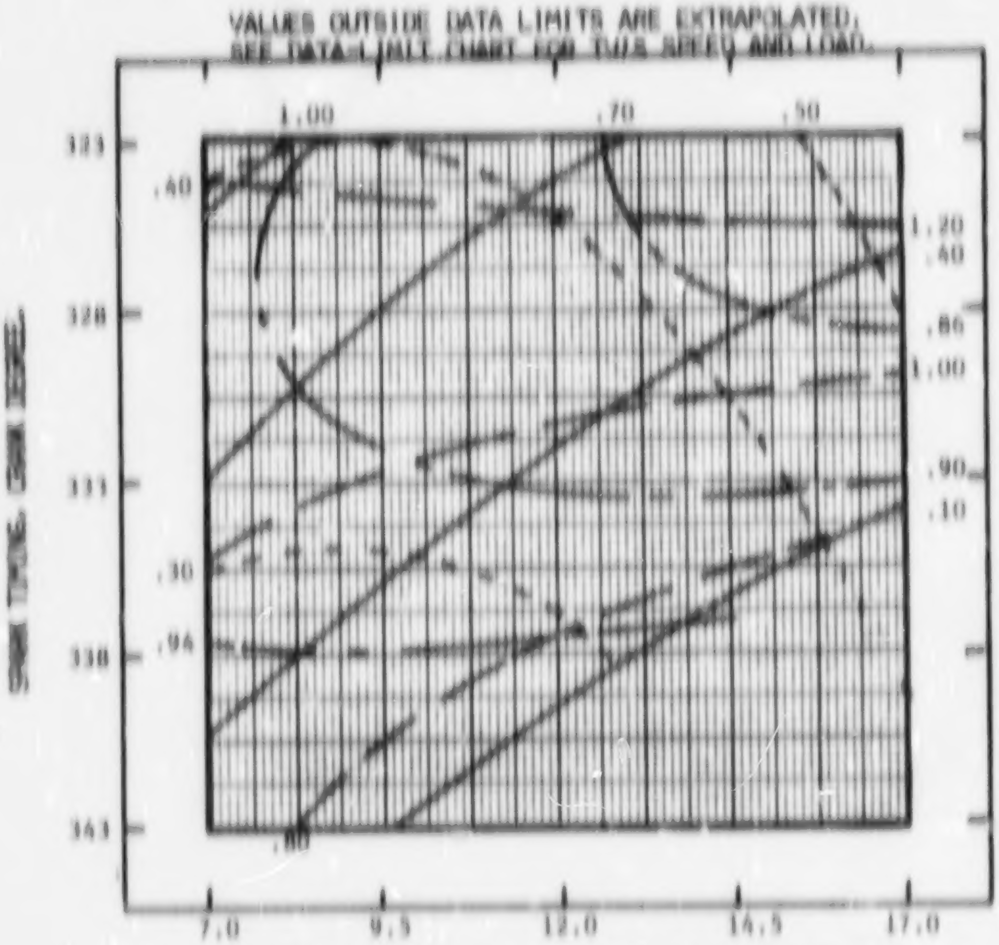
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO_2/HR.	▬▬▬	0.2708	1148 PPM NO	97.6
REL. # C_6/HR. (FID)	‒ ‒ ‒ ‒	0.4481	1074 PPM C_6	97.0
REL. # CO/HR.	- - - - - - -	2.5750	1.67 %	98.5
REL. # FUEL/BHPHR.	‒ ▬ ‒	0.7525		97.6

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

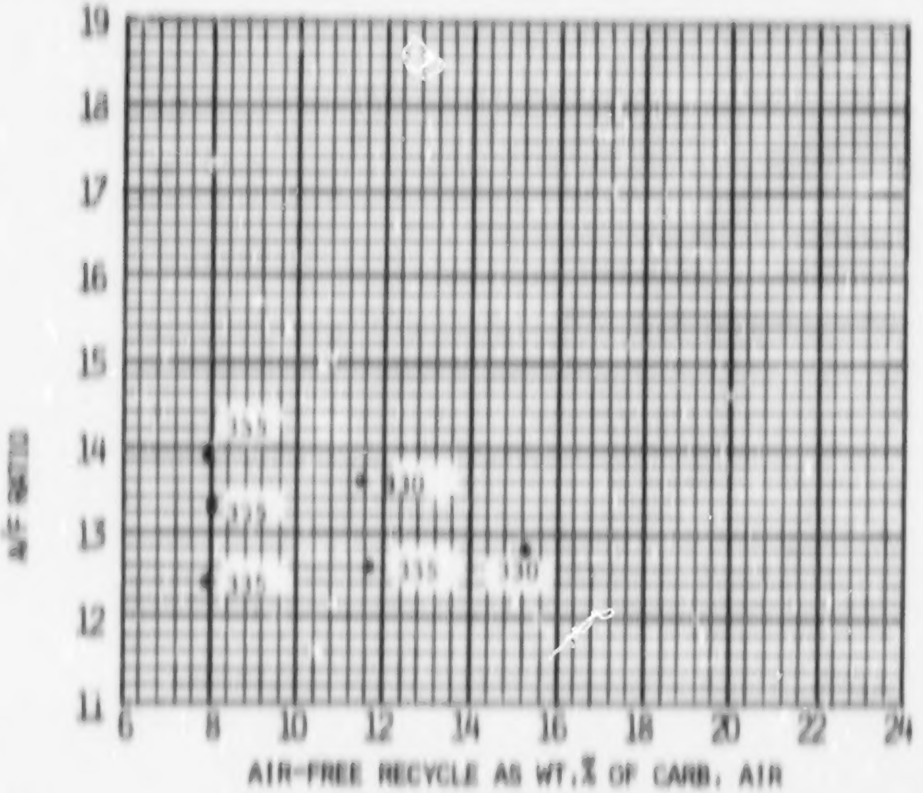
ENGINE: Chevrolet RPM: 1500 LB.-FT. TQ. 100

MFR'S A/F: 13.9/1 MFR'S. SPARK: 340 IMAP(1) 18.0 "HG.

CARB. AIR RATE(1) 1.77 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle
A/F 12.1-14.1
Spk. 340

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.121

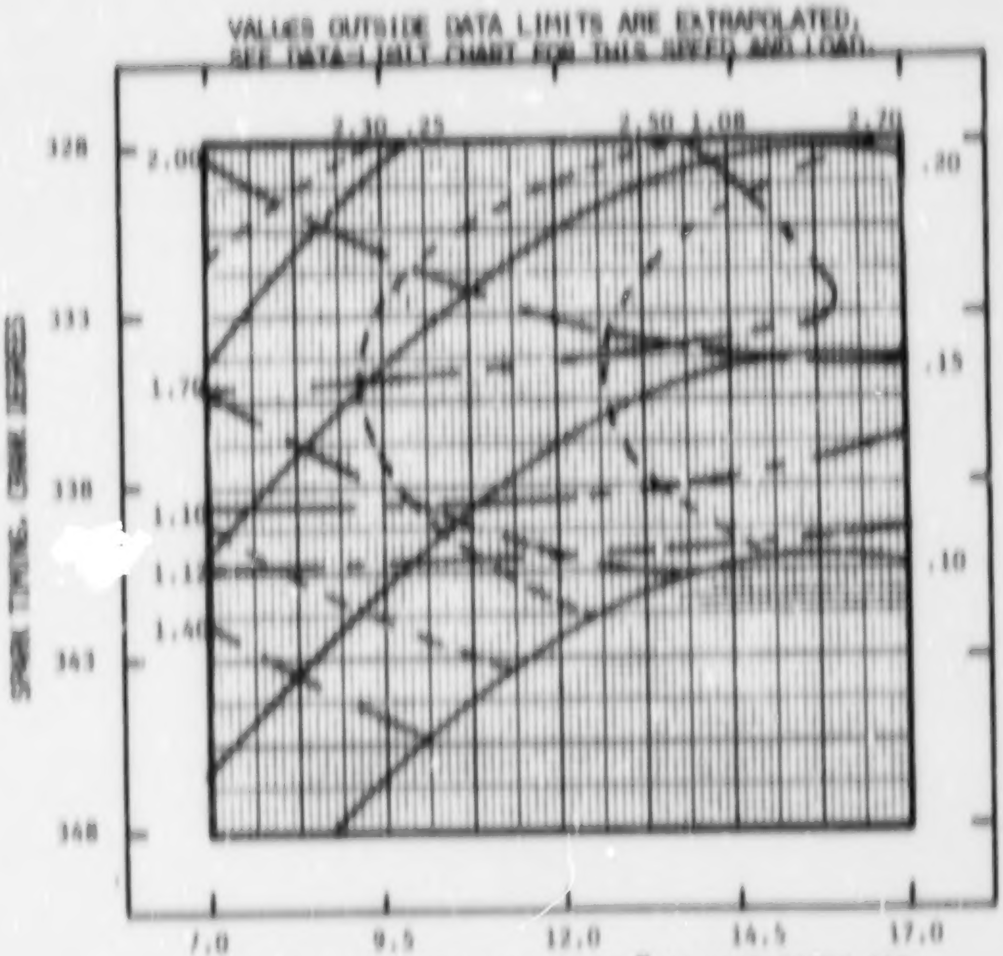
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 108
CONTROL SYSTEM A-1 A/F RATIO(2) 12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.5498	1592 PPM NO	95.7
REL. # C6HC/HR. (FID)	– – – –	0.5140	818 PPM C6	59.6
REL. # CO/HR.	=======	3.3640	1.57 %	53.6
REL. # FUEL/BHPHR.	– — –	0.5652		98.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.127

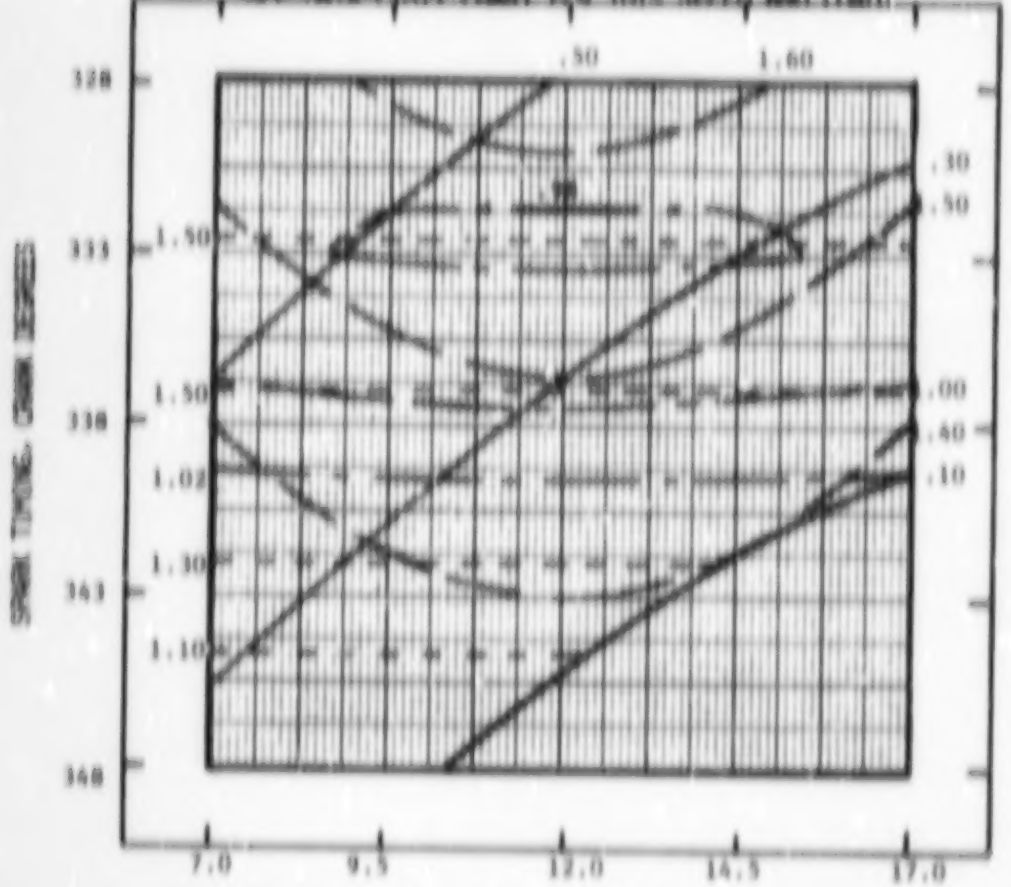
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.5498	1592 PPM NO	95.7
REL. # C6HC/HR. (FID)	= = = =	0.5160	818 PPM C6	89.6
REL. # CO/HR.	-------	3.3640	1.57 %	91.8
REL. # FUEL/BHPHR.	= — =	0.5652		98.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.123

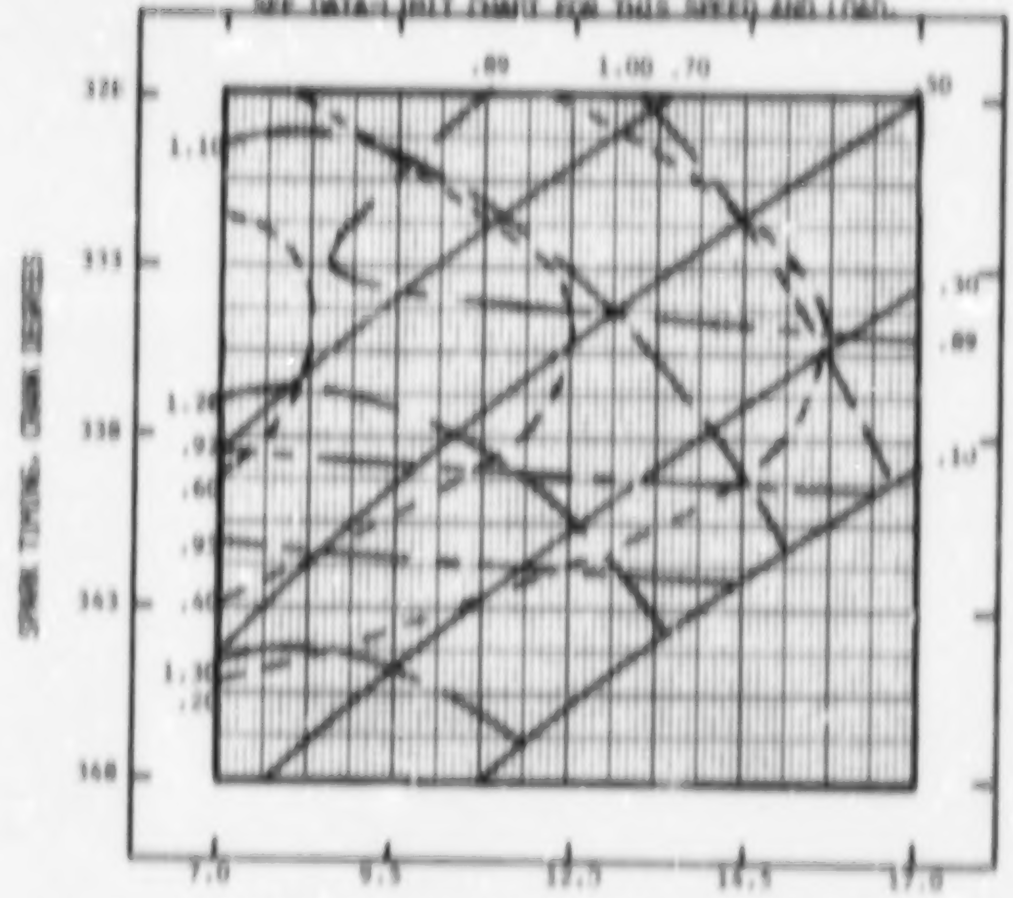
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 1500
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



Note: No test data obtained near this A/F.

AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.5698	1397 PPM NO	95.7
REL. # C6H14/HR. (FID)	– – – –	0.1160	818 PPM C6	89.6
REL. # CO/HR.	········	3.3640	1.57 %	93.6
REL. # FUEL/BHPHR.	– — –	0.5672		98.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.12A

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

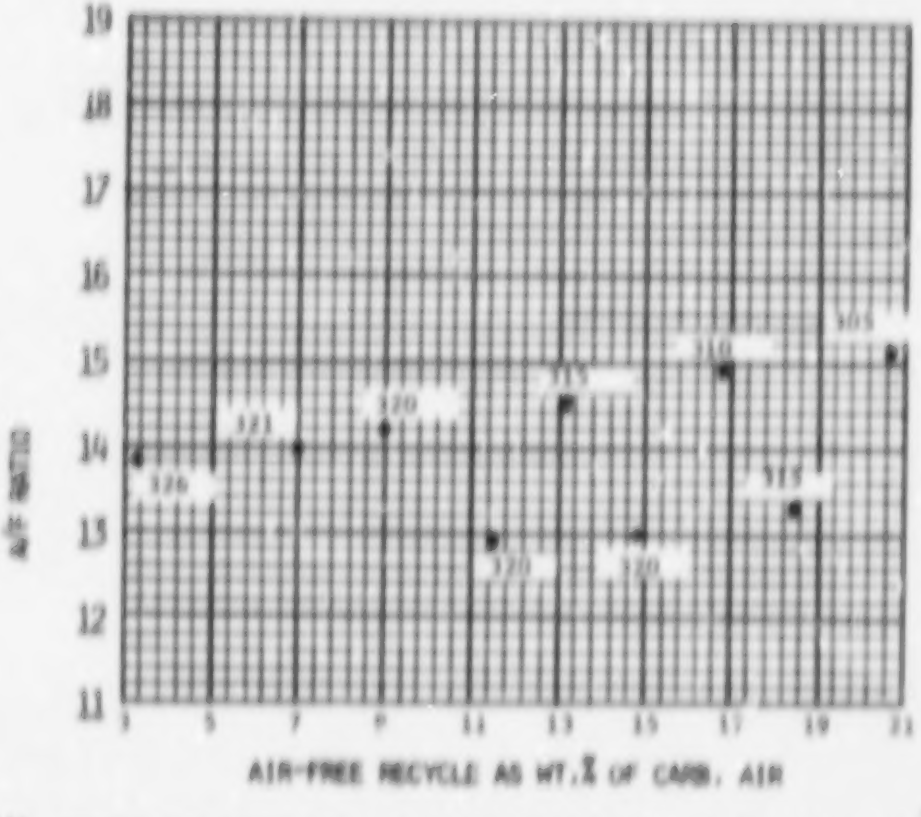
ENGINE: Chevrolet RPM: 2000 LB.-FT. TQ. 50

MFR'S A/F: 13.5/1 MFR'S. SPARK: 326 IMAP(1) 11.6 "HG.

CARB. AIR RATE(1) 3.19 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.5-13.5
Spk. 326

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A7.123

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

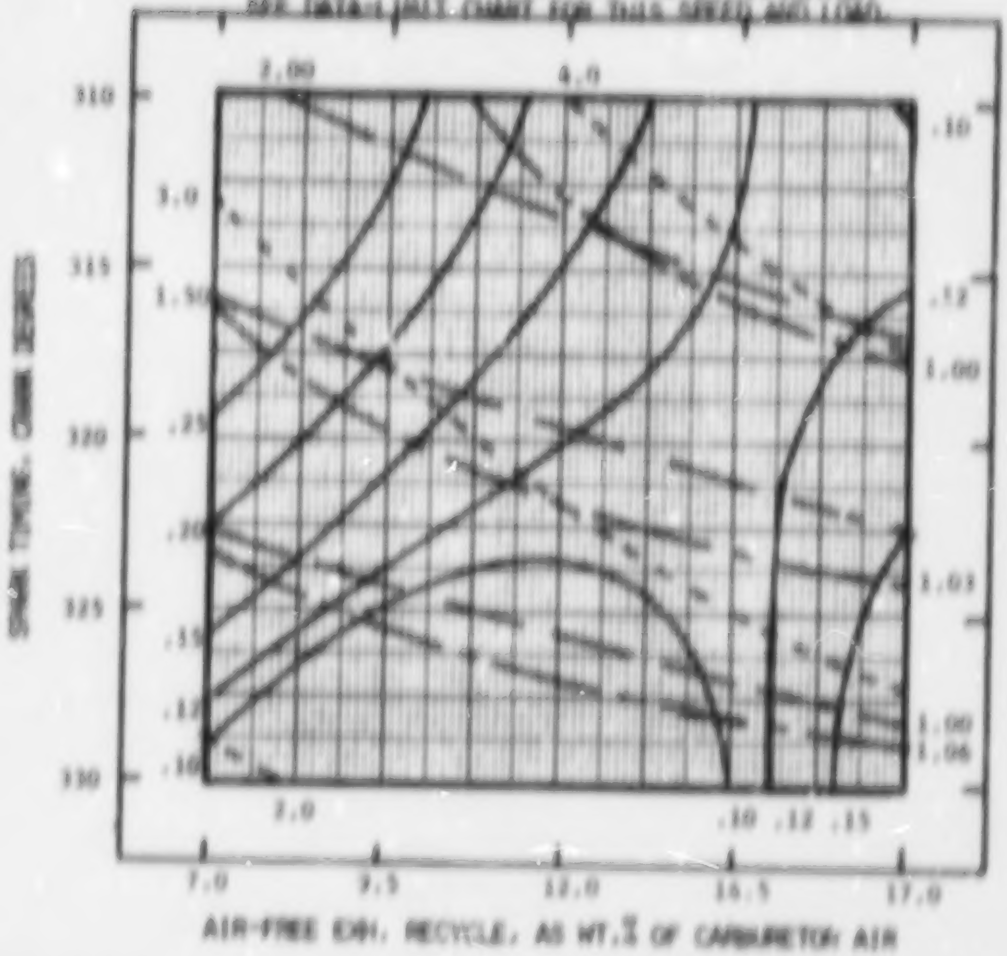
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000

CID 283 LB.-FT. TORQUE(1) 30

CONTROL SYSTEM A-1 A/F RATIO(2) 12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



Note: No data obtained near this A/F.

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.3709	1216 PPM NO	97.9
REL. # C6H14/HR. (FID)	— — —	0.2531	453 PPM C6	99.2
REL. # CO/HR.	-------	2.0150	1.30 %	78.6
REL. # FUEL/BHP-HR.	— - —	0.7675		78.7
				98.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT RPM'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO2 = 15.0%.

FIGURE A1.126

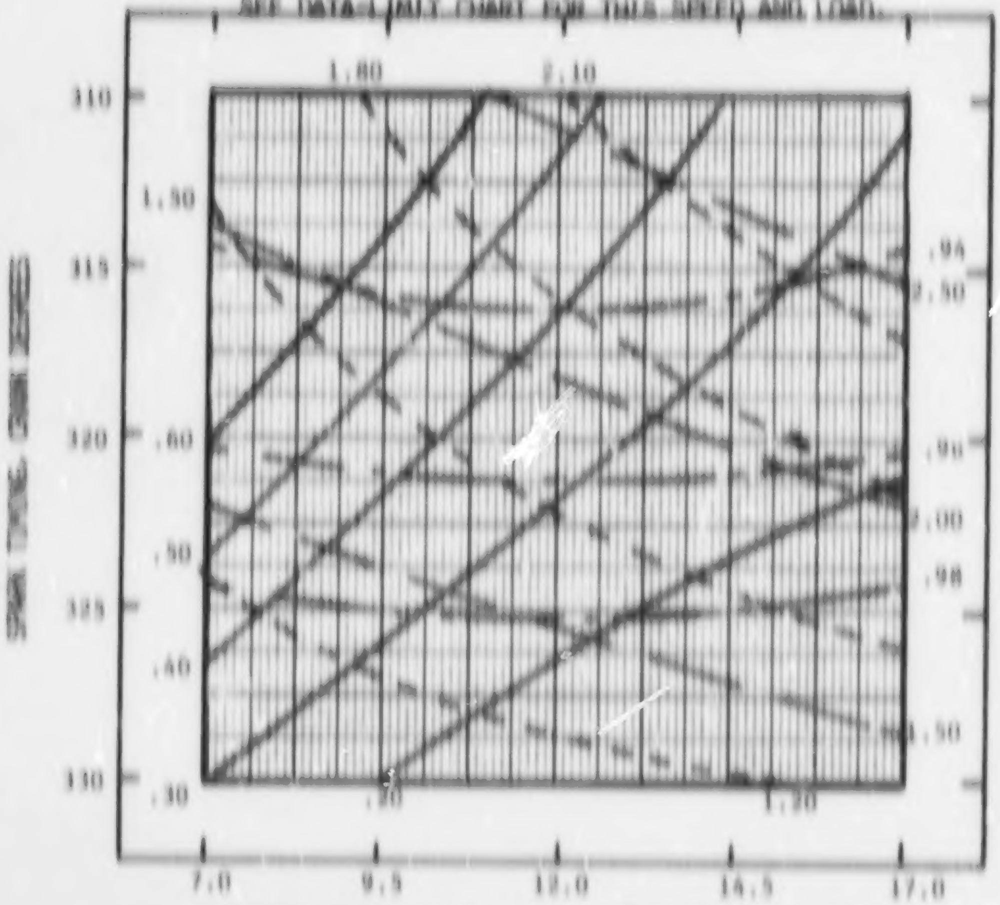
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.1709	1216 PPM NO	97.9
REL. # C6HC/HR. (FID)	= = = =	0.2531	455 PPM C6	99.3
REL. # CO/HR.	--------	2.0450	1.10 %	98.9
REL. # FUEL/BHPHR.	= — =	0.7425		98.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.
(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel
(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.127

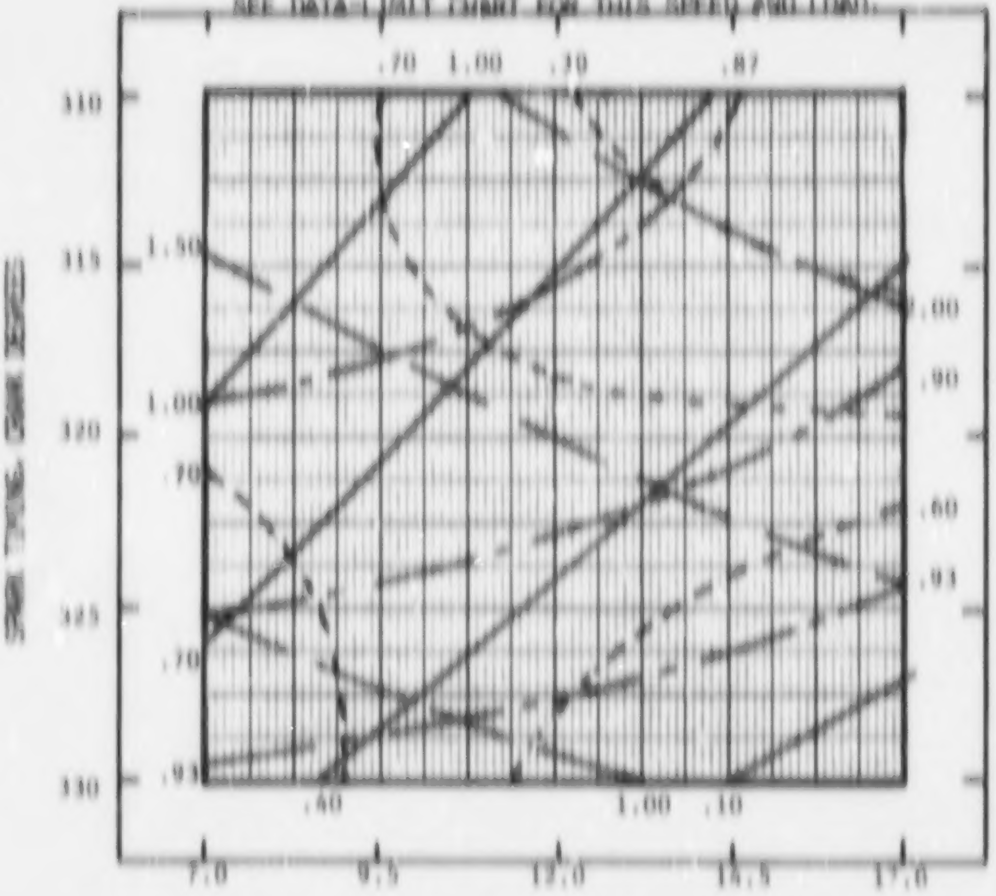
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 50
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.1709	1214 PPM NO	97.9
REL. # C6/HC/HR. (FID)	- - - -	0.2531	455 PPM C6	99.2
REL. # CO/HR.	-------	2.0430	1.10 %	98.9
REL. # FUEL/BHPHR.	- — -	0.7425		98.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.126

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

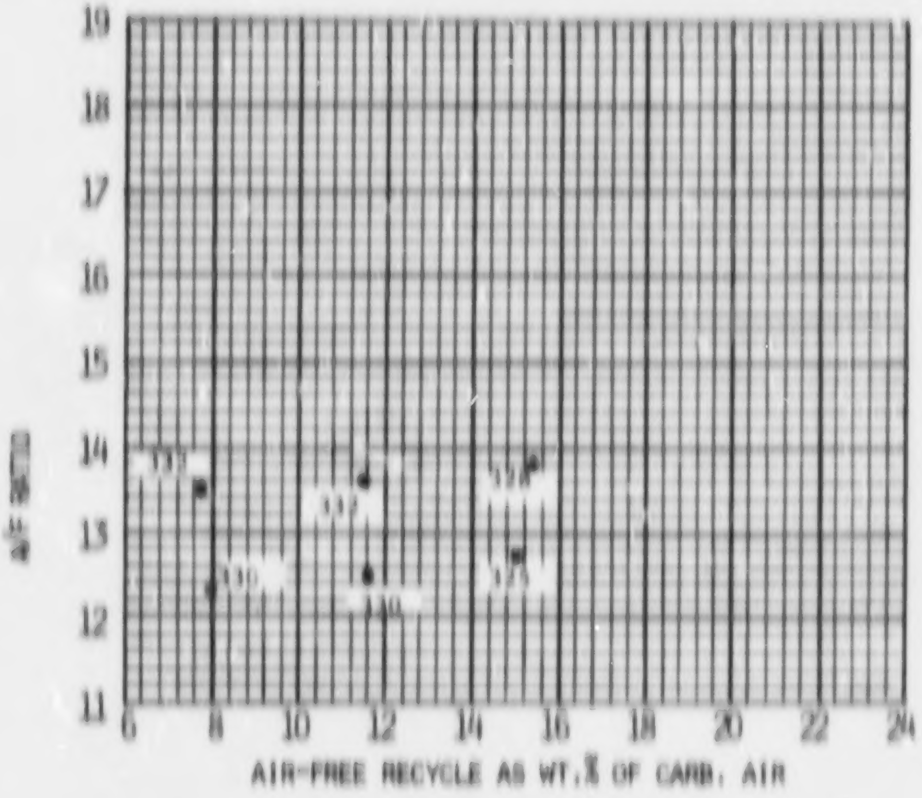
ENGINE: Chevrolet RPM: 2000 LB.-FT. TQ. 75

MFR'S A/F: 13.9/1 MFR'S. SPARK: 128 IMAP(1) 15.2 "HG.

CARB. AIR RATE(1) 5.19 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.0-14.0
Spk. 128

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.129

USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

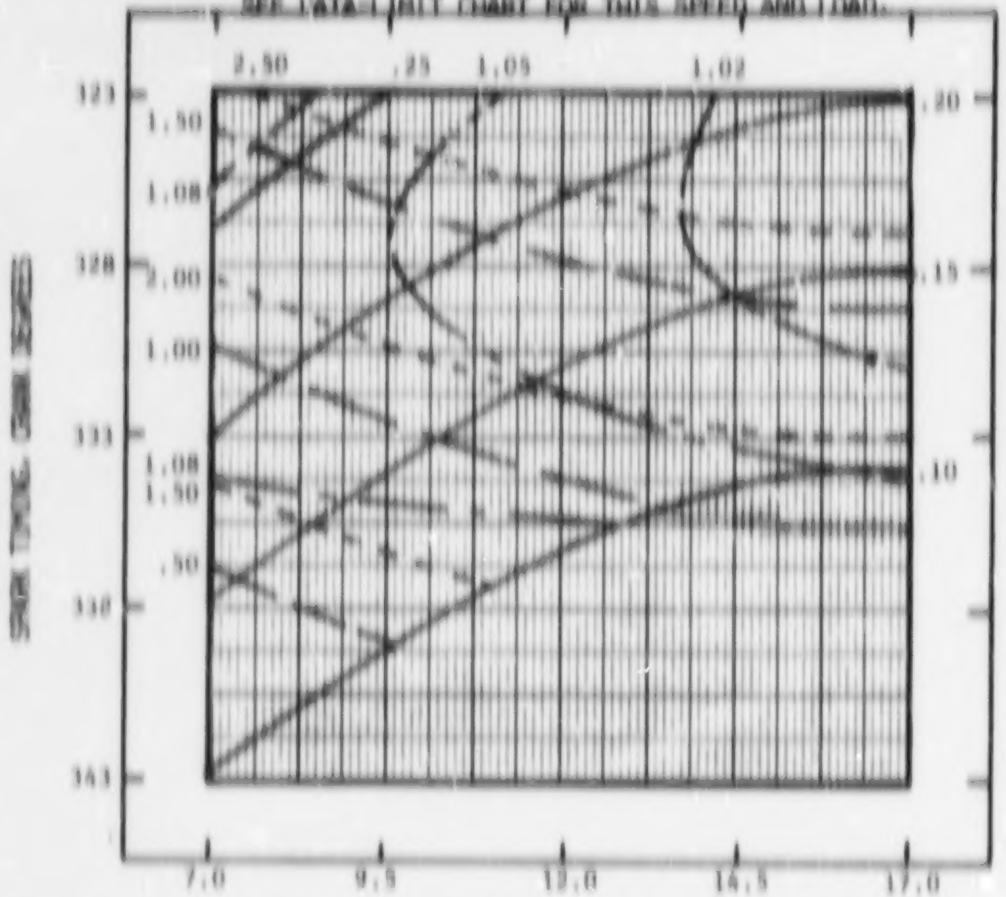
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000

CID 283 LB.-FT. TORQUE(1) 75

CONTROL SYSTEM A-1 A/F RATIO(2) 12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED. SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.7350	1900 PPM NO	99.1
REL. # C6HC/HR. (FID)	-- -- -- --	0.6763	673 PPM C6	99.0
REL. # CO/HR.	-- -----	3.3500	1.42 %	94.8
REL. # FUEL/BHPHR.	-- --- --	0.632		98.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.130

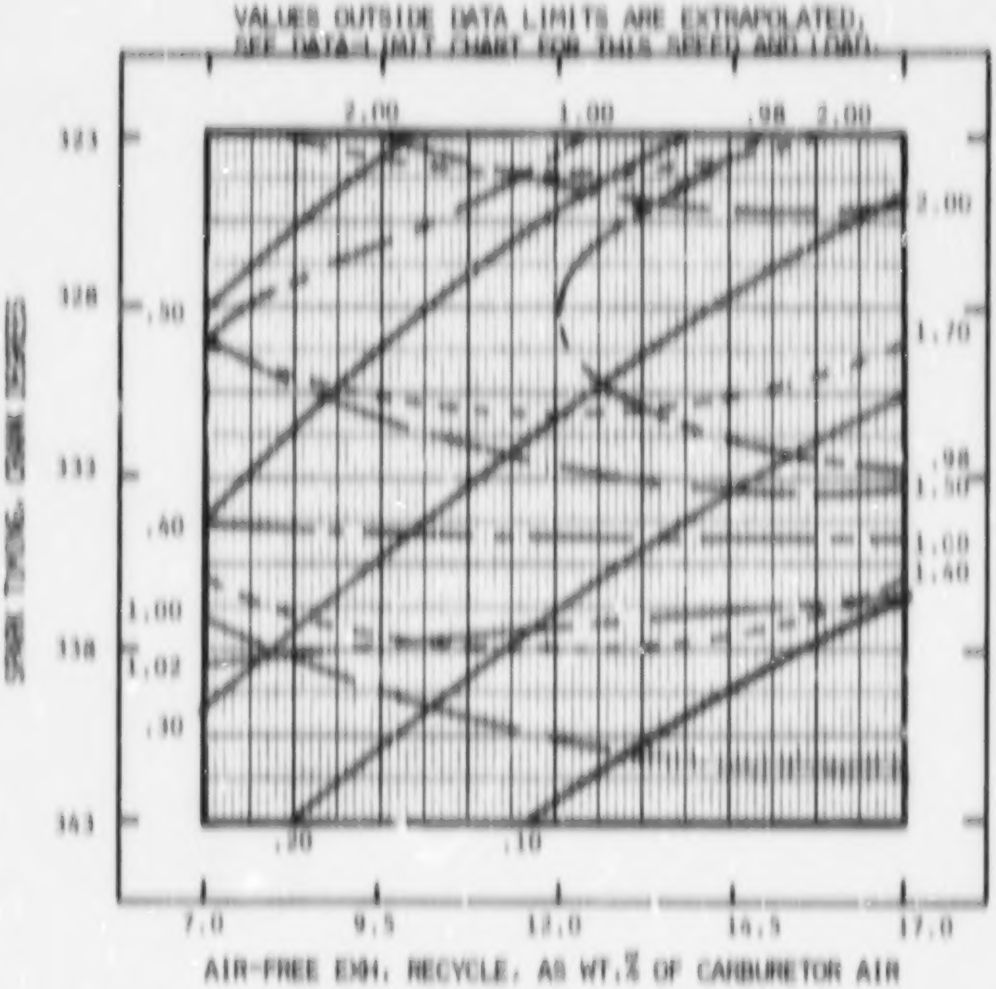
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE	Chevrolet	ENGINE RPM	2000
CID	283	LB.-FT. TORQUE(1)	25
CONTROL SYSTEM	A-1	A/F RATIO(2)	11.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.7350	1900 PPM NO	99.1
REL. # C6HC/HR. (FID)	‒ ‒ ‒ ‒	0.6763	673 PPM C6	99.0
REL. # CO/HR.	━━━ ‒	3.3200	1.42 %	94.8
REL. # FUEL/BHPHR.	‒ ━ ‒	0.6332		98.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.131

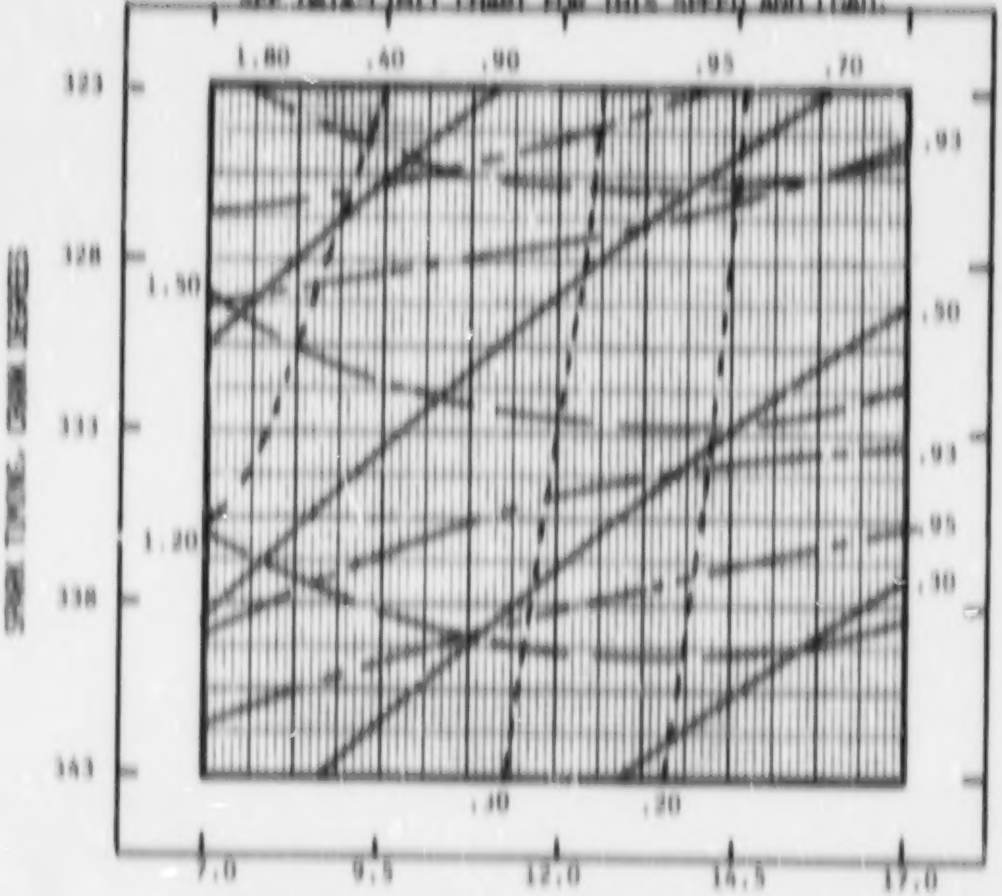
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 75
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



Note: No test data obtained near this A/F.

AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.7150	1900 PPM NO	99.1
REL. # C6HC/HR. (FID)	— — — —	0.6763	671 PPM C6	99.0
REL. # CO/HR.	-------	3.3500	1.41 %	96.8
REL. # FUEL/BHPHR.	- — -	0.6332		98.0

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

FIGURE A2.132

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

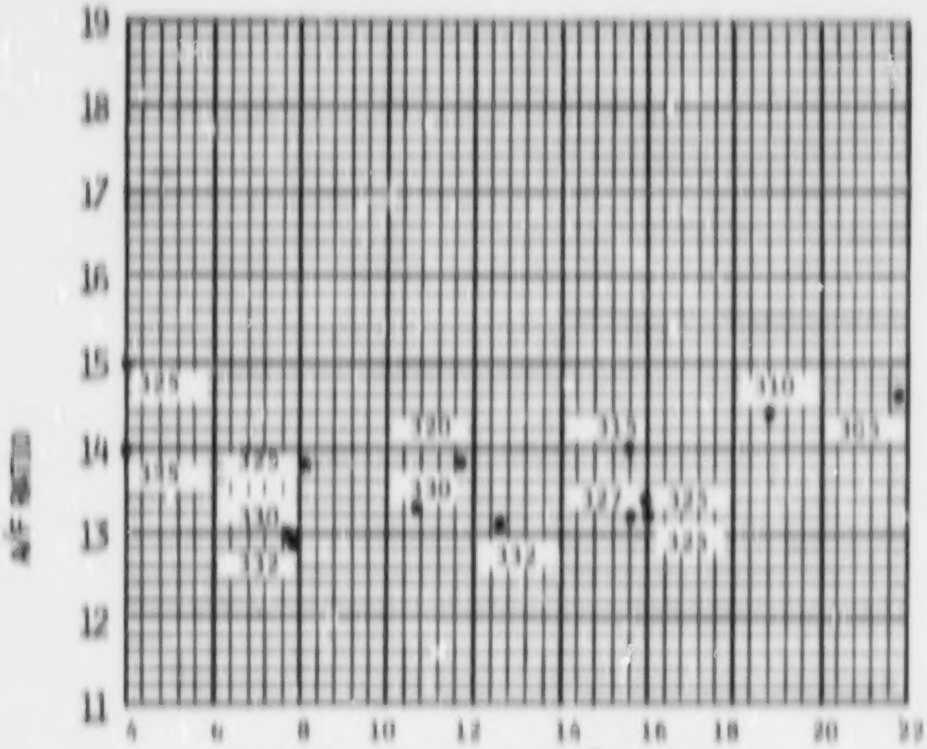
ENGINE: Chevrolet RPM: 2000 LB.-FT. TQ. 100

MFR'S A/F: 13.7 MFR'S. SPARK: 332 IMAP(1) 17.6 "HG.

CARB. AIR RATE(1) 4.94 LB./MIN.

* *

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



AIR-FREE RECYCLE AS WT.% OF CARB. AIR

Data for
Zero Recycle
A/F 12.6-14.9
Spk. 332

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.133

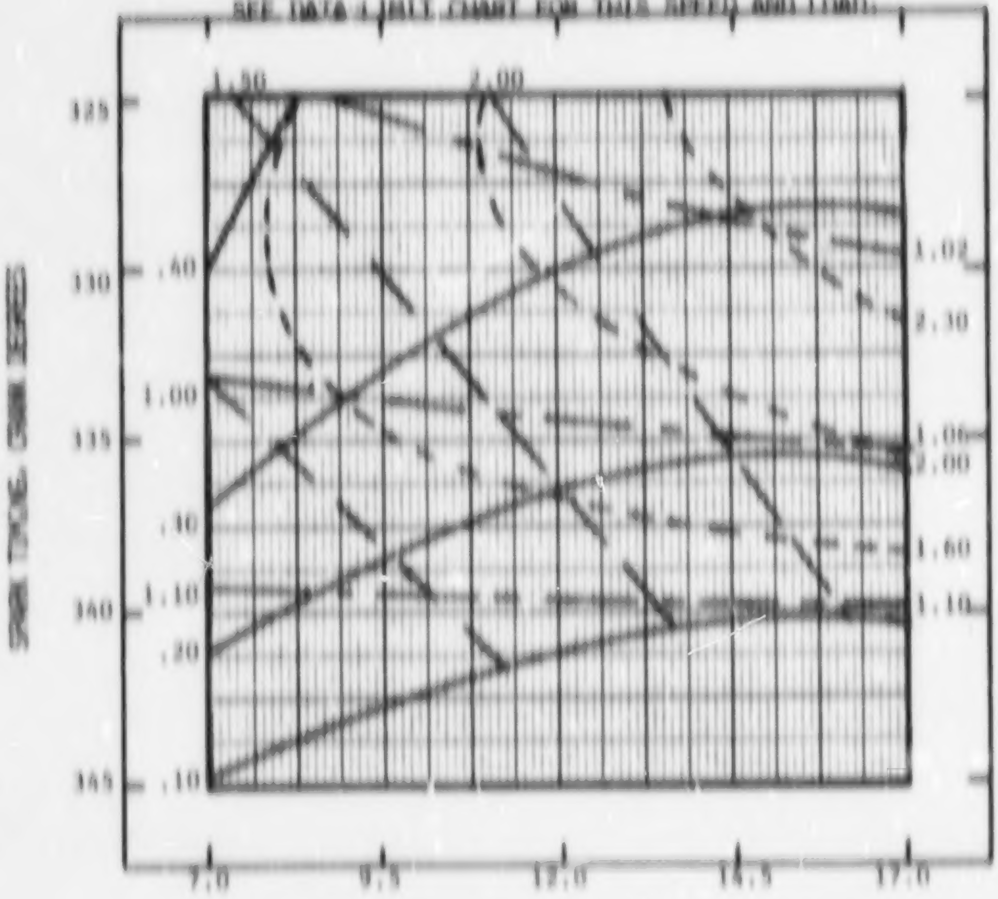
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 11.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	0.7995	1718 PPM NO	98.6
REL. # C6C/HR. (FID)	- - - -	0.6498	531 PPM C6	92.9
REL. # CO/HR.	········	5.0900	1.44 %	91.6
REL. # FUEL/BHPHR.	— — —	0.5675		96.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.13A

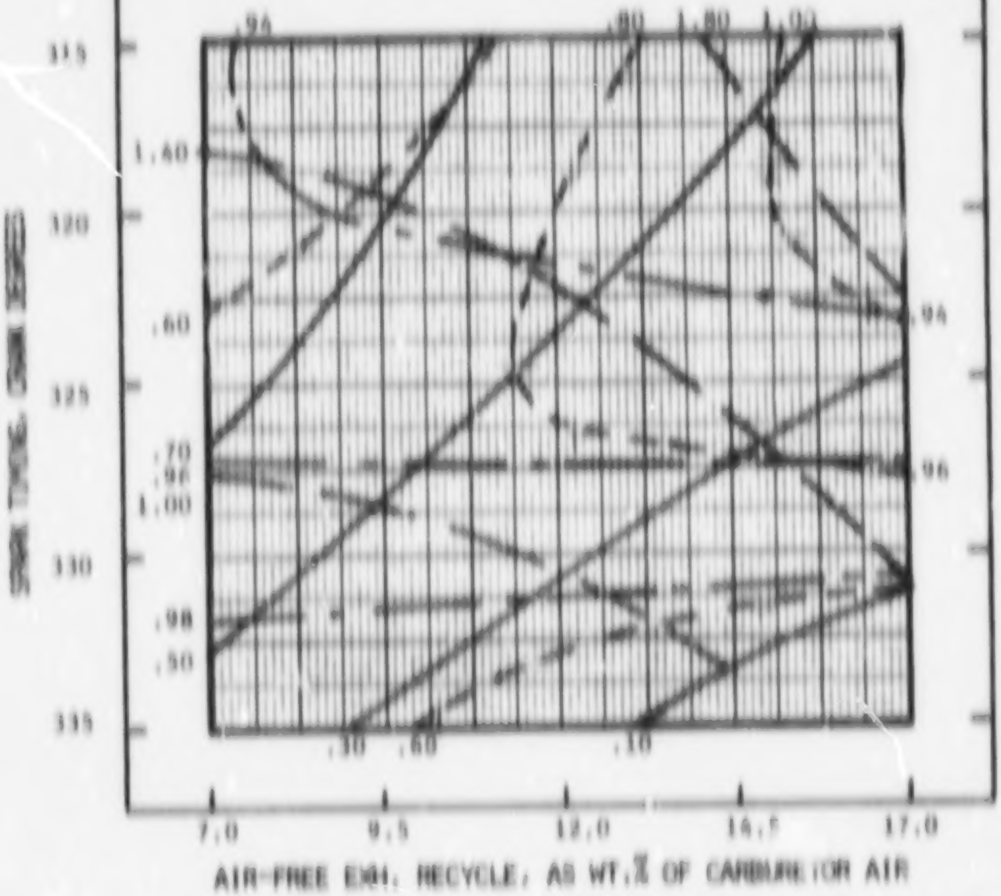
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 14.0

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.7995	1718 PPM NO	98.6
REL. # C6HC/HR. (FID)	– – – –	0.4498	331 PPM C_6	92.9
REL. # CO/HR.	--------	4.0900	1.45 %	97.4
REL. # FUEL/BHPHR.	– — –	0.5675		96.5

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

FIGURE A2.135

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

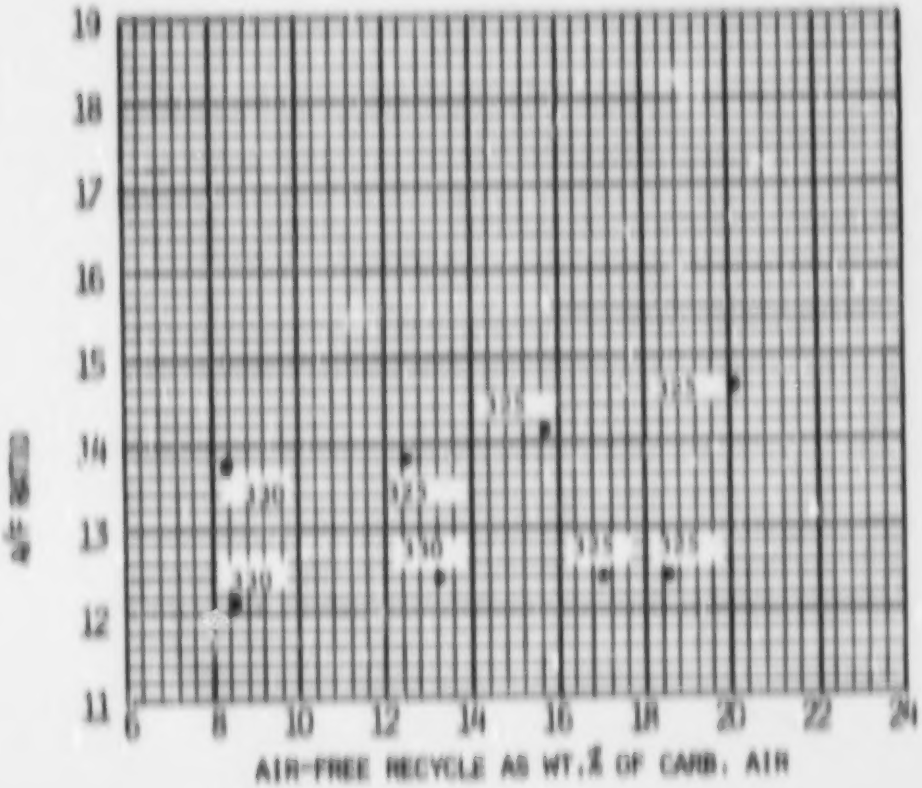
ENGINE: Chevrolet RPM: 2000 LB.-FT. TQ. 140

MFR'S A/F: 13.8 MFR'S. SPARK: 360 IMAP(1) 21.9 "HG.

CARB. AIR RATE(1) 6.21 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.0-13.8
Spk. 360

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

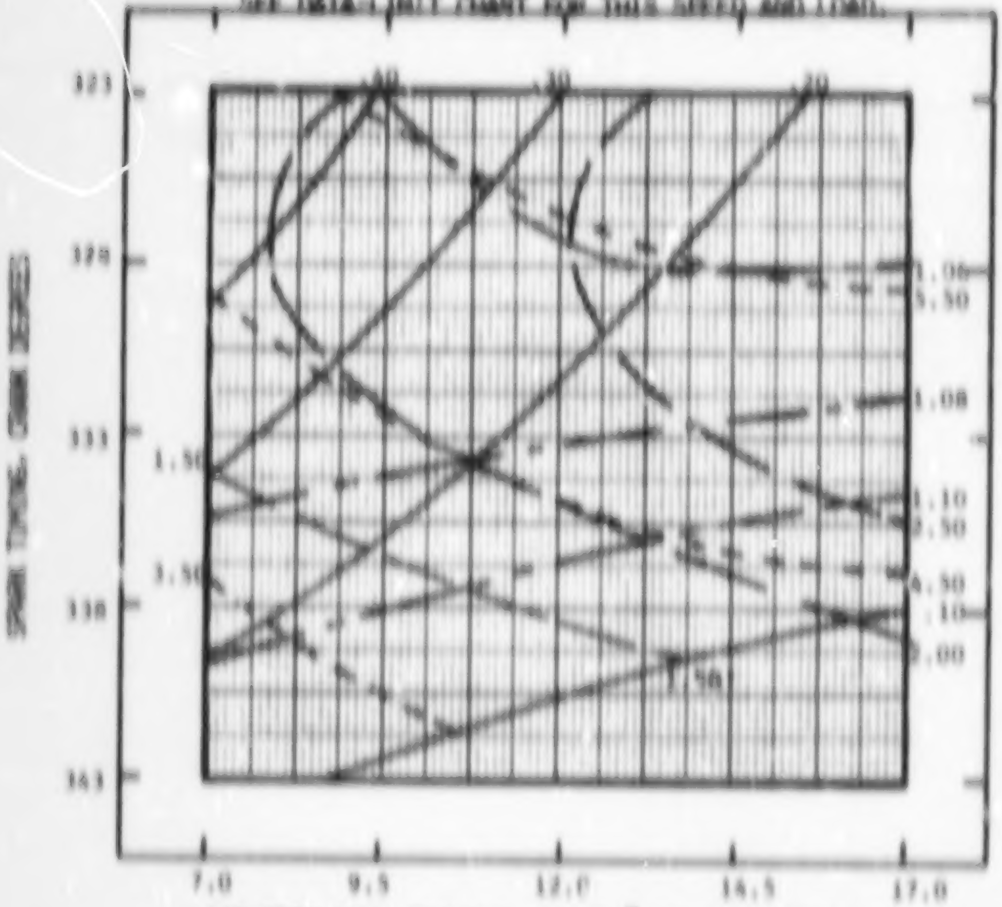
(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

FIGURE A2.136

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet
ENGINE RPM 2000
CID 283
LB.-FT. TORQUE(1) 140
CONTROL SYSTEM A-1
A/F RATIO(2) 12.3

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED; SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	0.8816	1689. PPM NO	97.8
REL. # C6H14/HR. (FID)	– – – –	0.6598(4)	423(4)PPM C6	98.6
REL. # CO/HR.	--------	1.9830	0.82 %	86.2
REL. # FUEL/BHPHR.	– — –	0.5081		98.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO2 = 15.0%.

(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

FIGURE A2.137

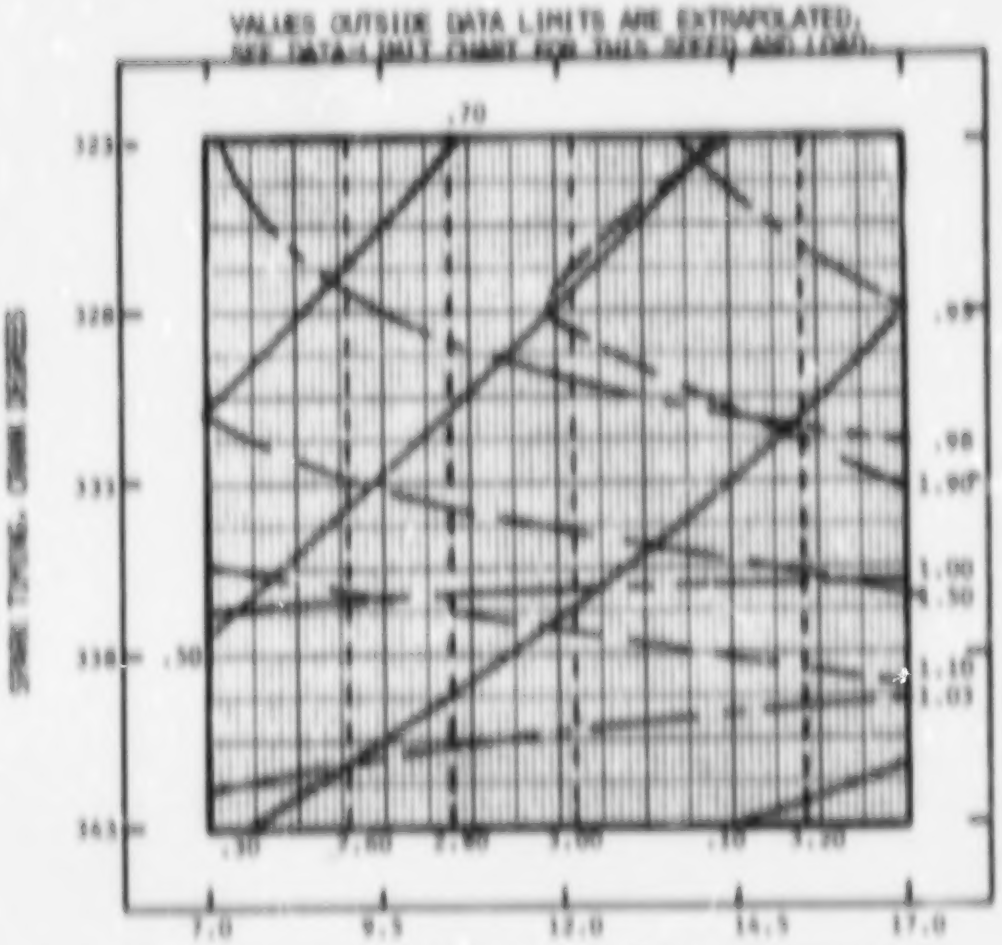
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 140
CONTROL SYSTEM A-1 A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED,
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━━━	0.8816	1409 PPM NO	97.0
REL. # C6H14/HR. (FID)	◦ ◦ ◦ ◦	0.0398(4)	577(4) PPM C6	98.6
REL. # CO/HR.	┅┅┅┅	7.9850	0.82 %	86.2
REL. # FUEL/BHPHR.	━ ━━ ━	0.5081		98.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO CO + CO_2 = 15.0%.

A-1541

(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

FIGURE A2.130

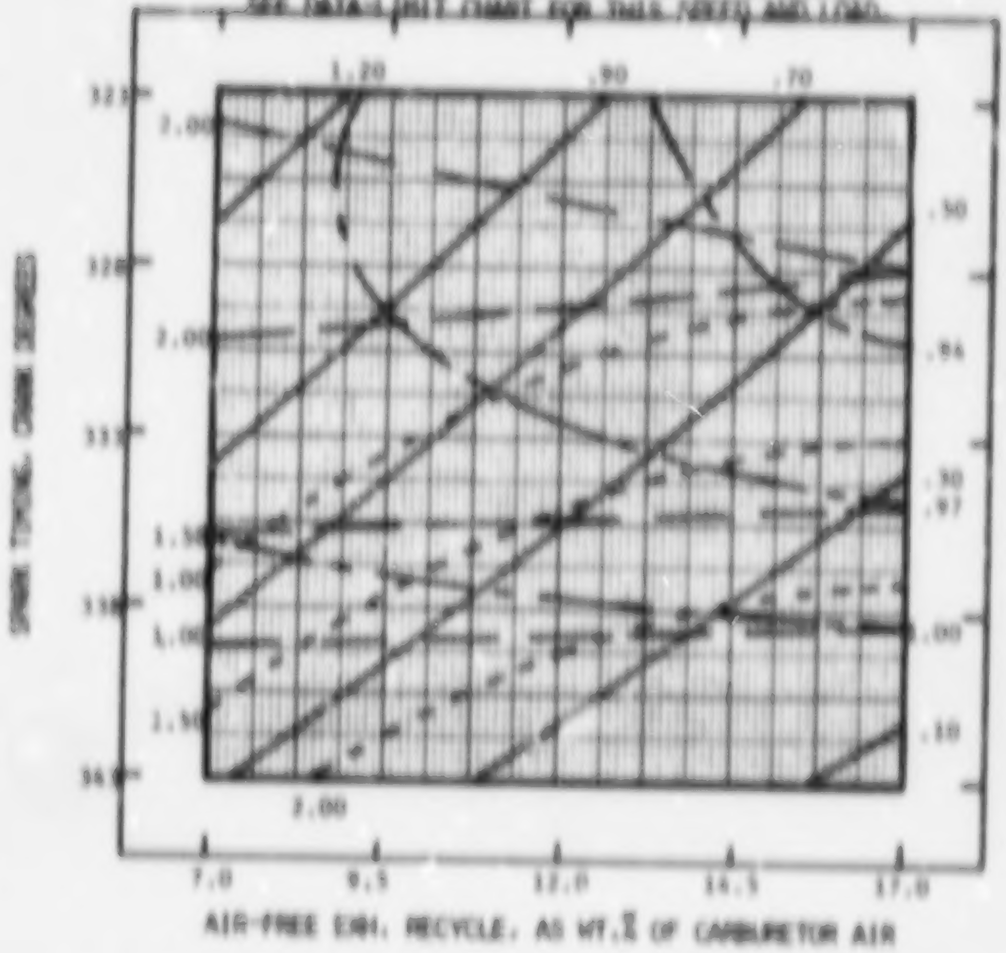
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2000
CID 283 LB.-FT. TORQUE(1) 160
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED, SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



Note: No test data obtained near this A/F.

	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	━━	0.0816	1509 PPM NO	97.8
REL. # C6H14/HR. (FID)	– – – –	0.1698(4)	473(4) PPM C6	98.6
REL. # CO/HR.	-------	2.9830	0.82 %	86.7
REL. # FUEL/BHPHR.	– — –	0.5581		[illegible]
				98.9

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT RPM'S, A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

FIGURE A2.139

USPHS EXHAUST-RECYCLE PROGRAM
DATA-LIMIT CHART

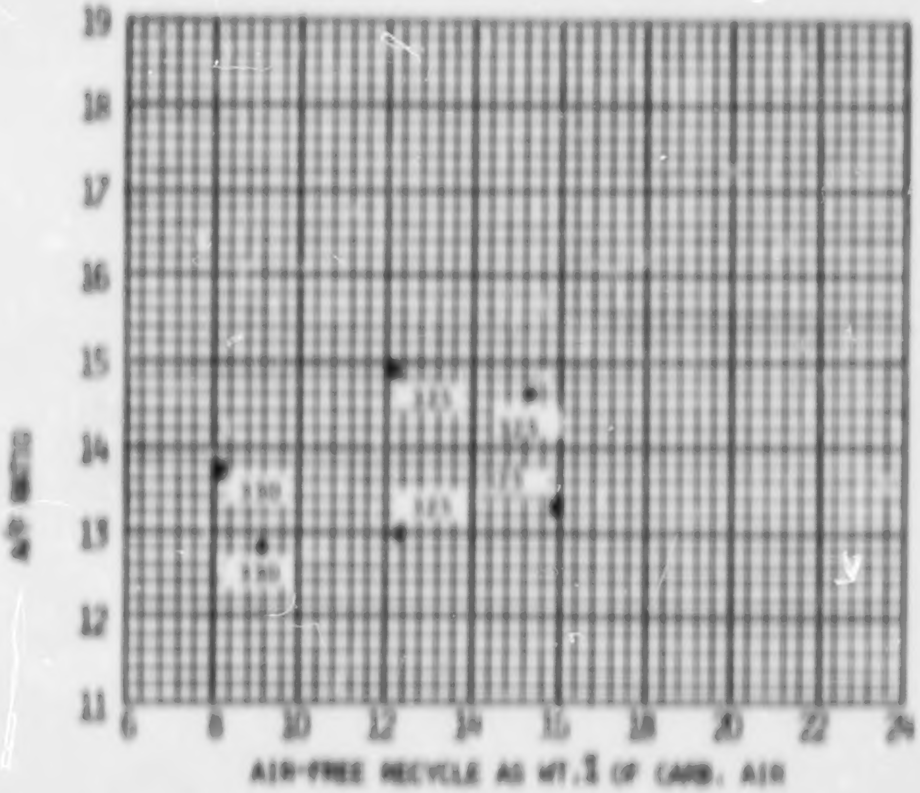
ENGINE: Chevrolet RPM: 2100 LB.-FT. TQ. 100

MFR'S A/F: 13.1 MFR'S. SPARK: 130 IMAP(1) 12.3 "HG.

CARB. AIR RATE(1) 3.75 LB./MIN.

- -

CHART SHOWS MOST-ADVANCED SPARK USED(2) AT EACH A/F RATIO AND % RECYCLE (AIR-FREE) TESTED AT THIS SPEED AND LOAD. BASIS FOR A/F IS DEFINED ON CONTOUR MAPS. DATA FROM MISFIRE CONDITIONS (MARKED M) WERE EXCLUDED FROM REGRESSION-EQUATION INPUT DATA.



Data for
Zero Recycle

A/F 12.6-14.1
Spk. 130

(1) TORQUE AND SPEED ARE SET AT MANUFACTURER'S A/F AND SPARK, NO RECYCLE. IMAP AND CARB. AIR ARE RECORDED. SPEED AND CARB. AIR ARE HELD CONSTANT AT OTHER A/F, SPARK, AND RECYCLE.

(2) MOST-ADVANCED SPARK IS NEAR MBT UNLESS DETONATION-LIMITED AT LESS ADVANCE. DATA ALSO OBTAINED AT TWO RETARDED SPARK SETTINGS.

[illegible]

FIGURE A2.160

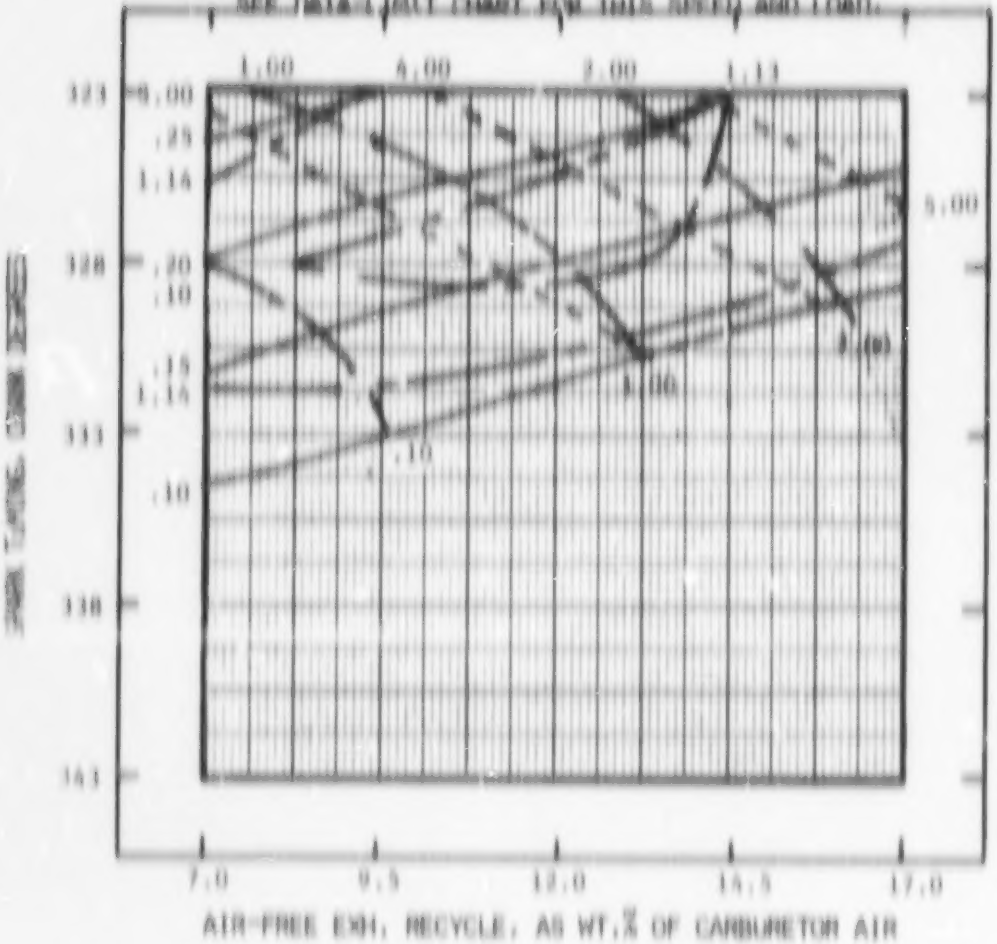
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2500
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 12.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	▬▬▬	1.1062	2104 PPM NO	91.2
REL. # C6HC/HR. (FID)	- - - -	0.4498(4)	447(4)PPM C6	93.4
REL. # CO/HR.	········	3.2590	0.99 %	85.6
REL. # FUEL/BHPHR.	– — –	0.5630		99.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2$ = 15.0%.

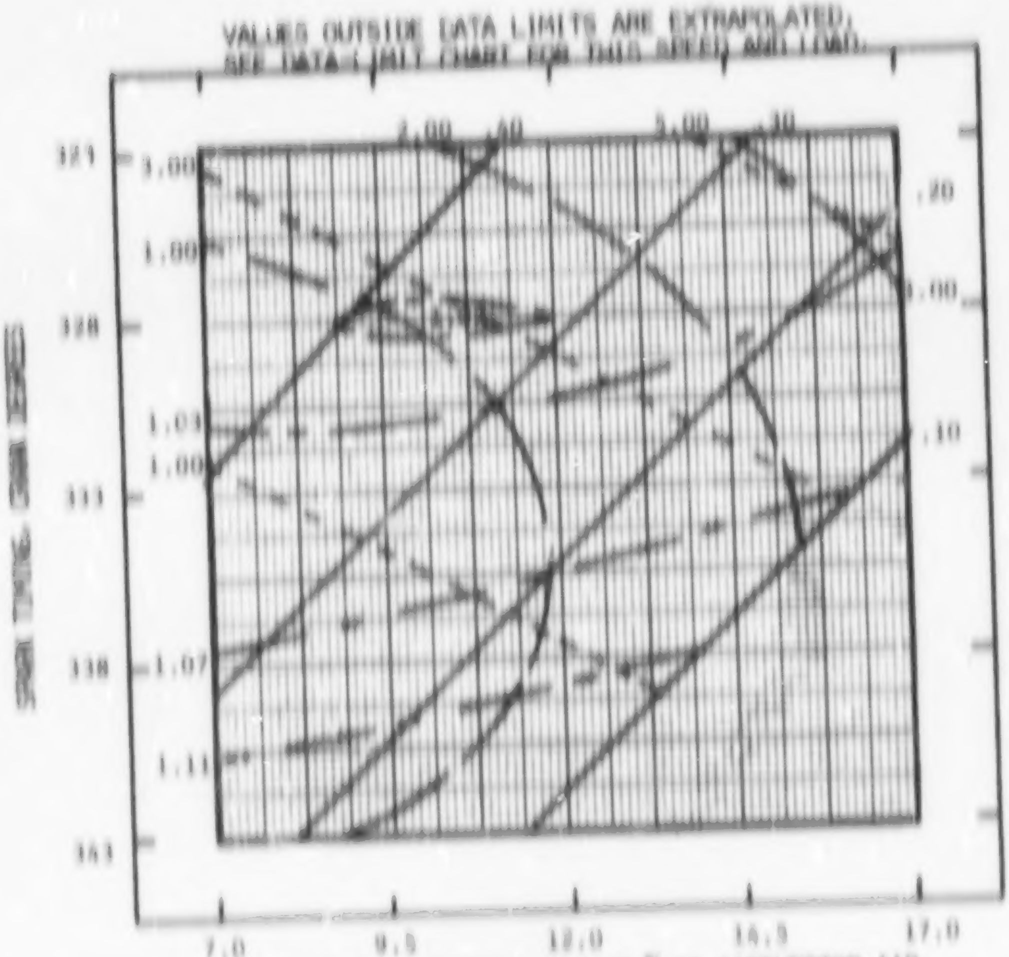
(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

FIGURE A2.141

USPHS EXHAUST-RECYCLE PROGRAM
STEADY-STATE ENGINE TESTS
DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet
CID 283
CONTROL SYSTEM A-1
ENGINE RPM 2500
LB.-FT. TORQUE(1) 100
A/F RATIO(2) 13.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



	CONTOUR LINE	BASE(3) #/HR.	BASE(3) CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3062	2106 PPM NO	93.2
REL. # C6HC/HR. (FID)	— — — —	0.4498(4)	427(4) PPM C6	93.4
REL. # CO/HR.	- - - - - - -	1.2390	0.99 %	85.6
REL. # FUEL/BHPHR.	— — —	0.3630		99.1

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

FIGURE A2.142

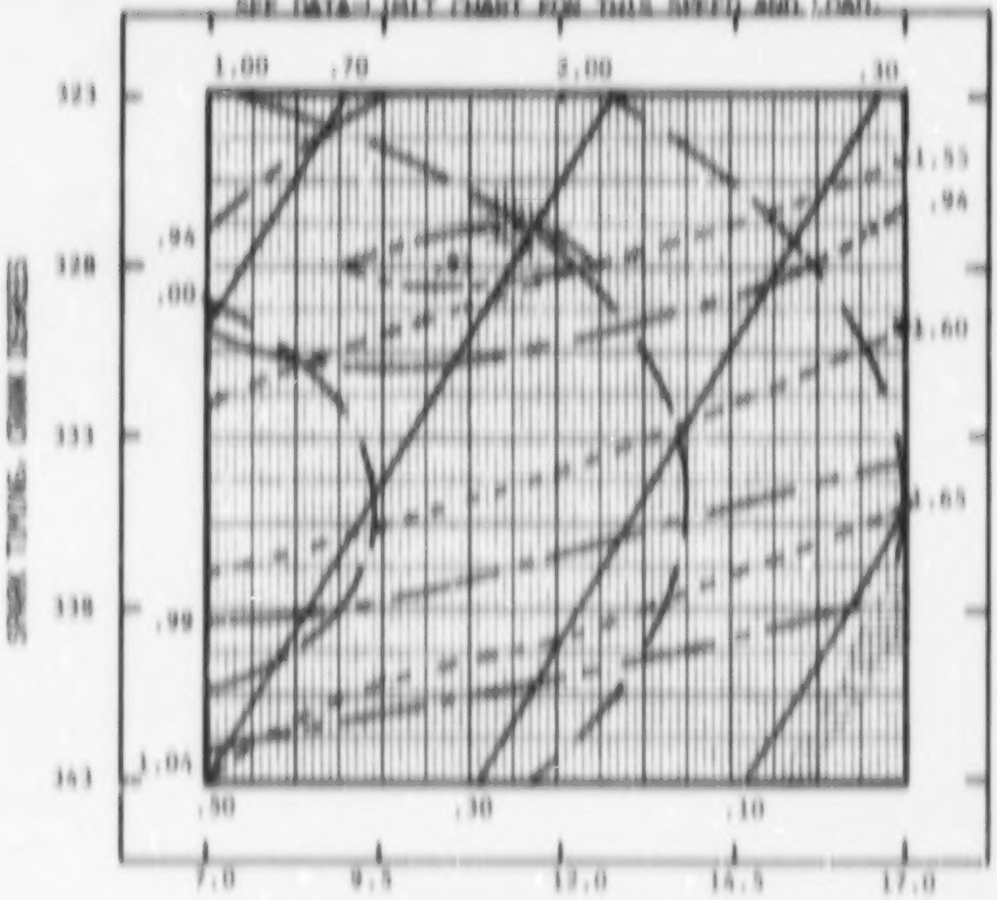
USPHS EXHAUST-RECYCLE PROGRAM

STEADY-STATE ENGINE TESTS

DATA CONTOURS COMPUTED FROM REGRESSION EQUATIONS

ENGINE Chevrolet ENGINE RPM 2500
CID 283 LB.-FT. TORQUE(1) 100
CONTROL SYSTEM A-1 A/F RATIO(2) 14.5

VALUES OUTSIDE DATA LIMITS ARE EXTRAPOLATED.
SEE DATA-LIMIT CHART FOR THIS SPEED AND LOAD.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

	CONTOUR LINE	BASE(3) #/HR.	CONC.	% DATA VARIANCE EXPL. BY REG. EQN.
REL. # NO2/HR.	———	1.3062	2106. PPM NO	91.2
REL. # C6HC/HR. (FID)	= = = =	0.4498(4)	327(4)PPM C6	93.6
REL. # CO/HR.	=======	3.2590	0.99 %	85.6
REL. # FUEL/BHPHR.	= == =	0.3630		99.3

(1) TORQUE AT BASE CONDITION DEFINES CONSTANT CARB-AIR RATE.

(2) A/F BASIS FOR DATA ANAL: (Carb. Air + Recycle Air)/Fuel

(3) MEAN VALUE AT MFR'S. A/F AND SPARK, NO RECYCLE; CONCENTRATIONS ADJUSTED TO $CO + CO_2 = 15.0\%$.

(4) Rate and conc. for HC based on rate = rate for 2000 RPM/100 tq.; actual values low because of abnormally hot exhaust under steady state.

A7.3 Interpretation of Regression Equations

Because of the large number of equations (148) and the variety of coefficients found to be significant, some simplification is required to permit examination of the effects of individual variables. This simplification has been done by averaging the coefficients of the equations for each dependent variable (Y_n) in each engine to yield B_0-B_9 coefficients for 16 within-engine average equations, corresponding to 4 dependent variables in 4 engines. The values for computing average coefficients may be composed, in some cases, of both negative and positive terms and may include an appreciable number of zeroes (non-significant coefficients). However, the important linear coefficients (B_1-B_3) are usually of consistent sign and fairly uniform magnitude for a given Y_n in a given engine, so that within-engine averaging appears reasonable in most cases.

Table A7.143, based on the coefficients of the 16 equations, shows the extent to which the main, or linear, effects of each variable are modified by the values of other variables, i.e., it evaluates the relative importance of the interaction terms and the linear terms.

The 16 within-engine average equations were then expanded to 48 reduced equations showing the effect, for a given engine and on a given dependent (Y) variable, of one independent (X) variable while the other independent variables are fixed at arbitrarily selected values. For these reduced equations, the fixed variables were assigned values of $X_1 = 0$, $X_2 = 0$, and/or $X_3 = X_{3_0}$ as appropriate, where X_{3_0} is the value of X_3 at zero recycle rate. Since $X_1 = 0$ and $X_2 = 0$ are fairly near the average manufacturer's base A/F ratio and spark in each engine, the reduced equations represent effects near the average base conditions, where $X_3 = X_{3_0}$. The reduced equations are listed in Tables A7.144-A7.146 and have the form of quadratic equations as follows:

- Equation for A/F effect:

$$Y = (\overline{B_0} + \overline{B_3}X_{3_0} + \overline{B_6}X_{3_0}^2) + (\overline{B_1} + \overline{B_8}X_{3_0})\ X_1 + \overline{B_4}X_1^2$$

- Equation for spark effect:

$$Y = (\overline{B_0} + \overline{B_3}X_{3_0} + \overline{B_6}X_{3_0}^2) + (\overline{B_2} + \overline{B_9}X_{3_0})\ X_2 + \overline{B_5}X_2^2$$

- Equation for recycle effect:

$$Y = \overline{B_0} + \overline{B_3}X_3 + \overline{B_6}X_3^2$$

Equating the first derivative to zero and solving for X_n locates the horizontal point (maximum or minimum) of each curve, with the results given in the tables. In a substantial number of reduced equations, the terms entering the averages are so heterogeneous, or the curvatures are so small, that the calculated horizontal points are meaningless or far outside the range of the data. These cases are noted in the tables; they dominate in the equations on spark and recycle effects, but are uncommon in those for A/F ratio effects. With very few exceptions, the linear effects and the remaining horizontal points are not only reasonable but in very good agreement with established trends between engine variables.

The contour maps showing the predicted results of California and USPHS driving cycles for the Plymouth with various spark schedules are presented in Figures A2.147-A2.152.

TABLE A7.14J

EVALUATION OF INTERACTIONS

Ratios of Average Interaction Coefficients to Average Linear Coefficients
(Without Regard to Sign)

Variable	Engine	$\bar{B}_7/\bar{B}_1$	$\bar{B}_7/\bar{B}_2$	$\bar{B}_8/\bar{B}_1$	$\bar{B}_8/\bar{B}_3$	$\bar{B}_9/\bar{B}_2$	$\bar{B}_9/\bar{B}_3$
NO	Valiant	0.426	0.392	0.445	0.386	0.538	0.508
	Chevrolet	1.198	0.577	1.185	0.878	0.114	0.175
	Ford	0.211	0.158	0.225	0.285	0.065	0.075
	Plymouth	0.125	0.084	0.164	0.133	0.082	0.098
HC	Valiant	0.177	0.086	0.819	0.721	0.000	0.000
	Chevrolet	0.669	1.196	1.077	0.573	0.059	0.099
	Ford	0.138	0.061	0.324	0.977	0.110	0.768
	Plymouth	0.121	0.163	0.058	1.165	0.020	0.289
CO	Valiant	0.467	0.410	0.663	1.096	0.000	0.000
	Chevrolet	0.563	1.196	0.326	1.457	0.191	0.407
	Ford	0.106	1.244	0.044	0.353	0.295	0.198
	Plymouth	0.073	1.269	0.014	0.114	0.362	0.159
BSFC	Valiant	0.152	0.268	0.206	0.268	0.023	0.017
	Chevrolet	0.051	0.068	0.068	1.000	0.238	5.235
	Ford	0.015	0.018	0.352	2.038	0.039	0.183
	Plymouth	0.306	0.362	0.389	0.667	0.169	0.260
Ratio evaluates: as a modifier of the		Spark (10 deg.)	A/F (1 unit)	% ER (5%)	A/F (1 unit)	% ER (5%)	Spark (10 deg.)
Linear Effects of:		A/F (1 unit)	Spark (10 deg.)	A/F (1 unit)	% ER (5%)	Sparks (10 deg.)	% ER (5%)

TABLE A2.144

REDUCED EQUATIONS FOR EFFECT OF A/F RATIO

Evaluated at $X_2 = 0$, X_{3_o} = Value at Zero Recycle.

Using Within-Engine Average Coefficients

Variable	Engine	Constant $\bar{B}_0 + \bar{B}_3 X_{3_o} + \bar{B}_6 X_{3_o}^2$	X_1 Coeff. $\bar{B}_1 + \bar{B}_8 X_{3_o}$	X_1^2 Coeff. $\bar{B}_4$	A/F for $X_1 = 0$ (1)	X_{3_o}	Properties of Curves
Y_1 (NO)	Valiant	0.9322	-0.3293	-0.0974	17.0	-2.2	NO max. at 15.36 A/F.
	Chevrolet	0.7987	+0.3983	+0.0143	13.5	-2.4	Nearly linear curve.
	Ford	1.1156	-0.0594	-0.0684	15.5	-3.0	NO max. at 15.07 A/F.
	Plymouth	0.9951	-0.0651	-0.0626	15.5	-3.0	NO max. at 14.98 A/F.
Y_2 (HC)	Valiant	0.9819	-0.4280	+0.2342	17.0	-2.2	HC min. at 17.91 A/F.
	Chevrolet	0.6450	+0.2439	-0.1052	13.5	-2.4	HC max. at 14.67 A/F. (2)
	Ford	1.1360	-0.0052	-0.0015	15.5	-3.0	HC max. at 14.80 A/F. (2)
	Plymouth	0.9853	-0.2562	+0.0990	15.5	-3.0	HC min. at 16.92 A/F.
Y_3 (CO)	Valiant	0.9884	-0.0267	+0.1357	17.0	-2.2	CO min. at 17.10 A/F.
	Chevrolet	0.4639	-0.1873	-0.0297	13.5	-2.4	CO max. at 10.35 A/F. (3)
	Ford	0.9365	-0.4944	+0.59..	15.5	-3.0	CO min. at 15.89 A/F.
	Plymouth	1.0031	-0.9892	+ .1079	15.5	-3.0	CO min. at 16.14 A/F.
Y_4 (BSFC)	Valiant	1.0036	+0.0626	+0.0388	17.0	-2.2	FC min. at 16.19 A/F
	Chevrolet	1.0218	-0.0297	+0.0136	13.5	-2.4	FC min. at 16.38 A/F
	Ford	0.9857	-0.0033	+0.0072	15.5	-3.0	FC min. at 15.73 A/F
	Plymouth	1.0123	-0.0302	+0.0209	15.5	-3.0	FC min. at 15.74 A/F

(1) Leaner ratios are positive, at 1.0 ratio = 1.0.

(2) Reasonable for air-injected engines where CO supports oxidation of HC, but questionable on basis of regression equations, which include both -, 0, and + terms for B_4

(3) Value is beyond data range and is of doubtful meaning.

A46675

TABLE A2.145

REDUCED EQUATIONS FOR EFFECT OF SPARK TIMING

Evaluated at $X_1 = 0$, $X_3 = \bar{X}_{3_c}$ = Value at Zero Recycle,

Using Within-Engine Average Coefficients.

Variable	Engine	Constant $\bar{B}_0 + \bar{B}_3 X_{3_c} + \bar{B}_8 X_{3_c}^2$	X_2 Coeff. $\bar{B}_2 + \bar{B}_9 X_{3_c}$	X_2^2 Coeff. $\bar{B}_5$	Spark (1) for $X_2 = 0$	Properties of Curves
Y_1 (HC)	Valiant	0.9522	-0.3829	+0.0006	325 deg.	Nearly linear (2).
	Chevrolet	0.7687	-0.2737	-0.0106	325	Nearly linear (2).
	Ford	1.1156	-0.2769	-0.0212	325	Nearly linear (2).
	Plymouth	0.9974	-0.2382	-0.0168	325	Nearly linear (2).
Y_2 (CO)	Valiant	0.9819	-0.3136	-0.0246	325	Max. outside data. (2)
	Chevrolet	1.6490	-0.4580	-0.0087	375	Nearly linear. (2)
	Ford	1.1160	-0.2733	-0.0580	325	Max. at 302, outside data.
	Plymouth	0.9853	-0.2166	-0.0351	325	Max. at 294, outside data.
Y_3 (NO)	Valiant	0.9884	+1.0456	—	325	Linear.
	Chevrolet	1.4679	-0.2208	-0.0952	335	Max. at 325, meaning ? (2)
	Ford	0.9295	+0.0843	—	325	Linear.
	Plymouth	1.0050	+0.0015	—	325	Linear.
Y_4 (BSFC)	Valiant	1.0038	+ .0661	-0.0093	325	Max. outside data (2).
	Chevrolet	1.0219	+ .1174	+0.0392	335	Min. FC at 320.
	Ford	0.9857	+0.0430	-0.0081	325	Nearly linear (2).
	Plymouth	1.0123	+0.0271	+0.0148	325	Min. FC at 316.

(1) Positive values are retarded, at 10 degrees = 1.0.

(2) Coefficients averaged into $\bar{B}_5$ are heterogeneous or largely zero.

TABLE A7.148

REDUCED EQUATIONS FOR EFFECT OF EXHAUST RECYCLE

Evaluated at $X_1 = 0$, $X_2 = 0$, Using Within-Engine Average Coefficients.

Variable	Engine	Constant $\bar{B}_0$	X_3 Coeff. $\bar{B}_3$	X_3^2 Coeff. $\bar{B}_6$	% ER for $X_3 = 0$(1)	Properties of Curves
Y_1 (HC)	Valiant	0.2874	-.1858	+0.0467	11	Min. HC at 20.45% ER(2)
	Chevrolet	0.2160	-0.1398	+0.0377	12	Min. HC at 21.27% ER (2)
	Ford	0.2981	-0.1455	+0.0422	15	Min. HC at 23.62% ER (2)
	Plymouth	0.2432	-0.1584	+0.0310	15	Min. HC at 27.78% ER (2)
Y_2 (CO)	Valiant	0.9344	+0.1734	+0.0721	11	Min. CO at 4.99%
	Chevrolet	1.1988	+0.3202	+0.0395	12	Min. at <0% ER (3)
	Ford	1.2957	+0.0799	—	15	Linear (3)
	Plymouth	1.1185	+0.0159	-0.0095	15	Nearly flat, little curvature.
Y_3 (NO)	Valiant	0.9836	+0.0352	+0.0170	11	Min. at 5.82% (3)
	Chevrolet	1.5375	+0.1938	-0.0360	12	Max. at 25.38% (3)
	Ford	0.8964	-0.0465	-0.0186	15	Max. at 6.06% (3)
	Plymouth	0.7443	-0.1274	-0.0125	15	Max. at <0% ER (3)
Y_4 (BSFC)	Valiant	1.0799	+0.0931	+0.0266	11	Min. FC at 2.25% ER
	Chevrolet	1.0086	+0.0134	+0.0037	12	Min. FC at 9.70% ER
	Ford	1.0007	+0.0104	+0.0011	15	Min. at <0% ER (3)
	Plymouth	1.0243	+0.0259	+0.0106	15	Min. FC at 6.55% ER

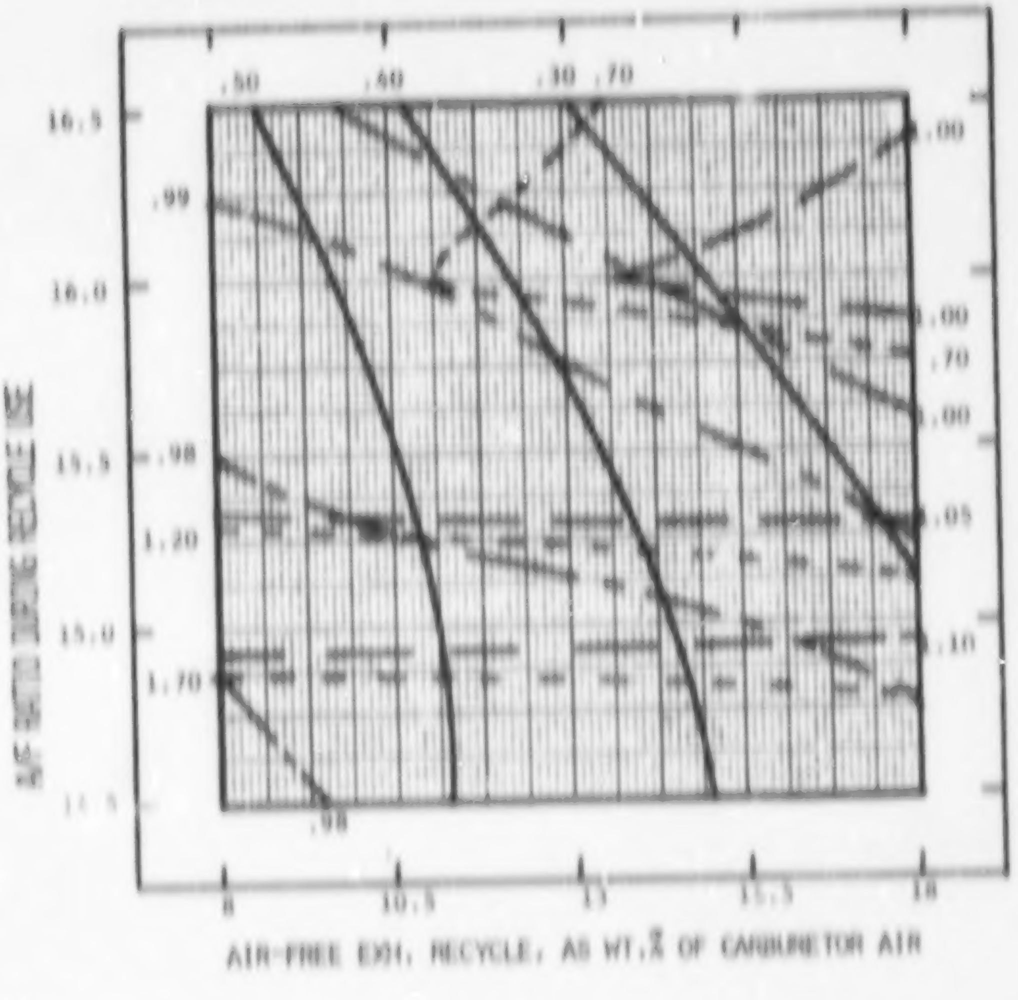
(1) Positive values increase at 5% = 1.0.
(2) Minima reflect curvature at lower % ER, are probably not real.
(3) Values averaged for $\bar{B}_6$ include both + and - terms, or are mostly zero; inflections of doubtful significance.

FIGURE A2.147

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN California DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mod-2



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS,
FOR ENTIRE CYCLE. (Counted seconds only).

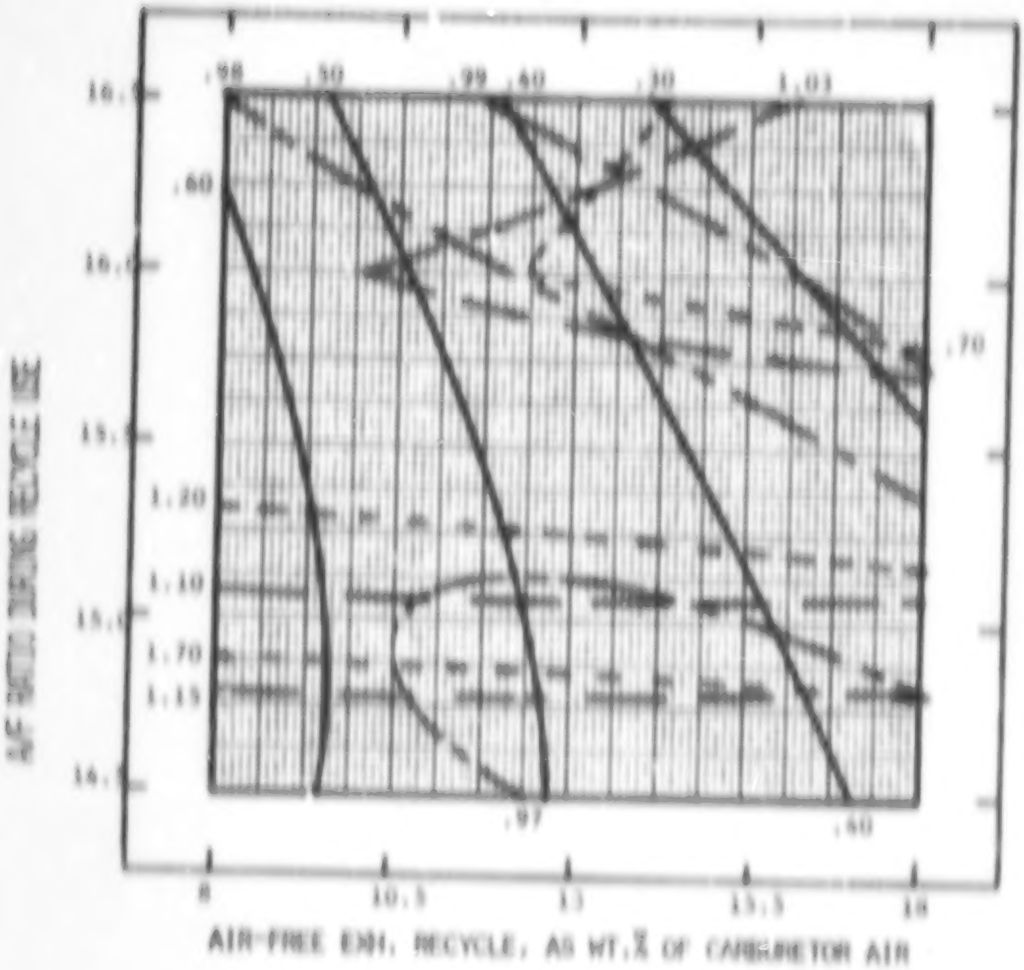
NOx
HC (FID)
FUEL CONS.
CO [illegible]

FIGURE A2.14A

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN California DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mod-1



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE. (Counted seconds only).

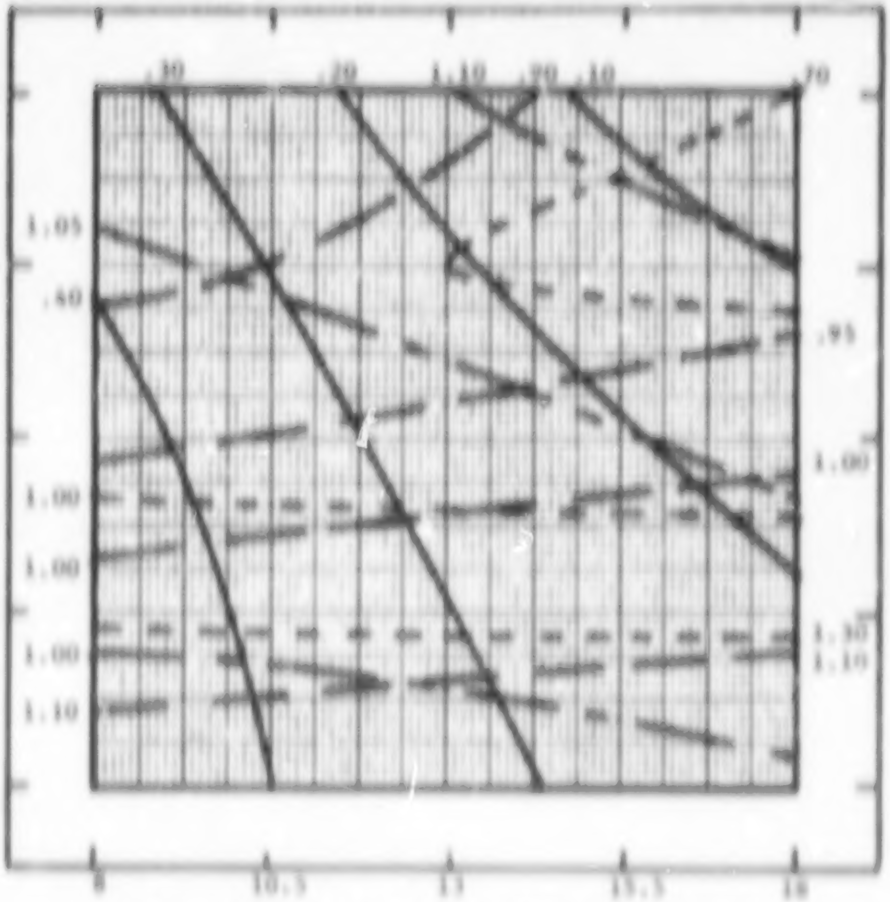
———————— NOx
—— —— —— HC (FID)
—— - —— - —— - FUEL CONS.
- - - - - - - - CO

FIGURE A2.149

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN USPHS DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mfr - Std.



AIR-FREE EXH. RECYCLE, AS WT.% OF CARBURETOR AIR

EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE.

——————— NOx
— — — HC (FID)
— - — - — FUEL CONS.
- - - - - - CO

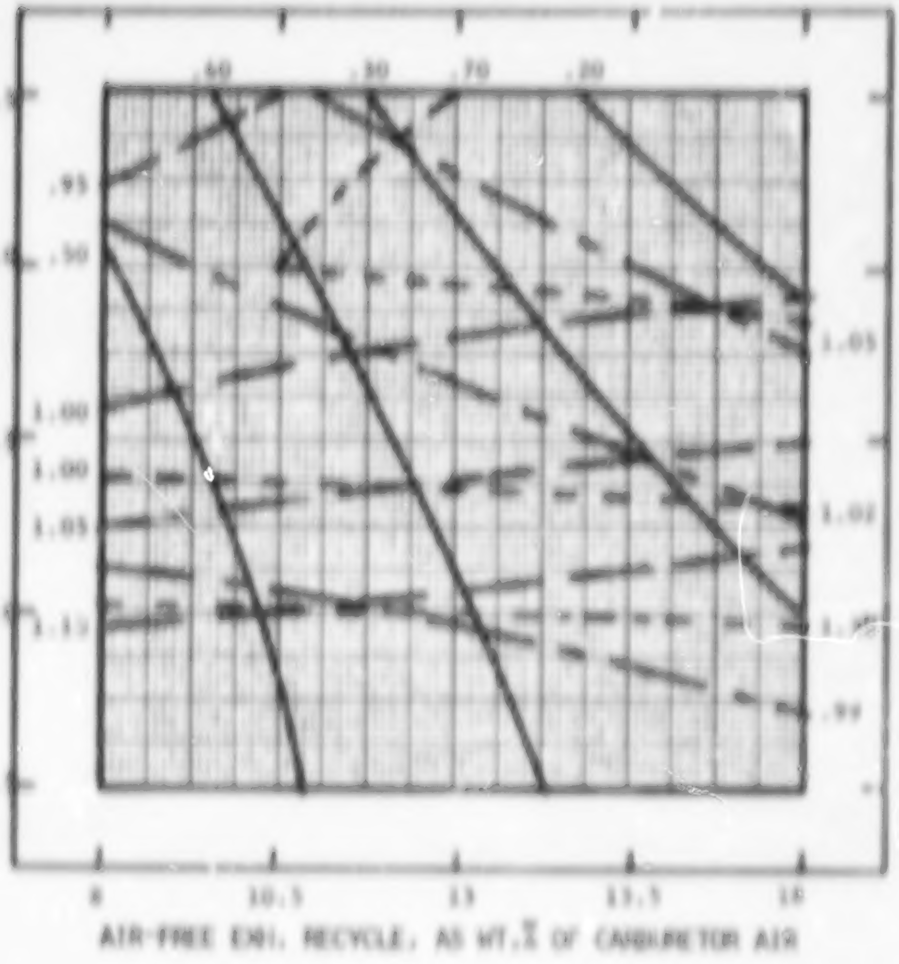
FIGURE A2.139

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR

Plymouth VEHICLE IN USPHS DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mod-1



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE.

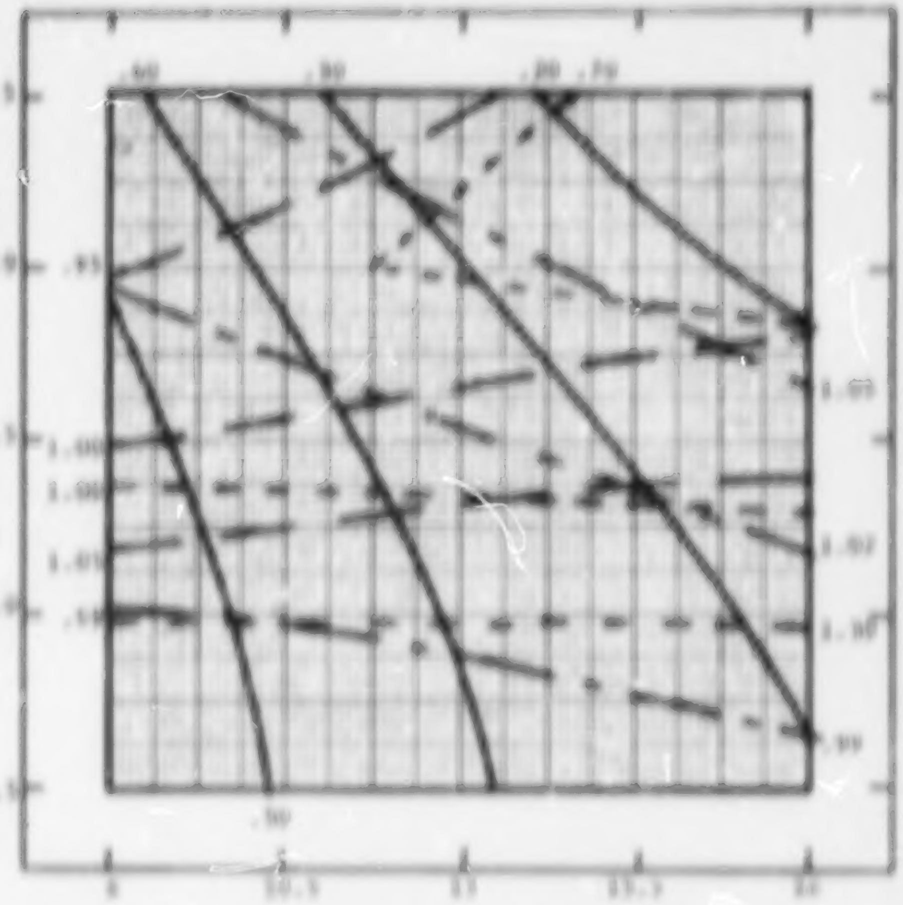
———————	NOx
—— —— ——	HC (FID)
—— - —— - ——	FUEL CONS.
- - - - - - - -	CO

FIGURE A7.131

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN [illegible] DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mod-1



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE.

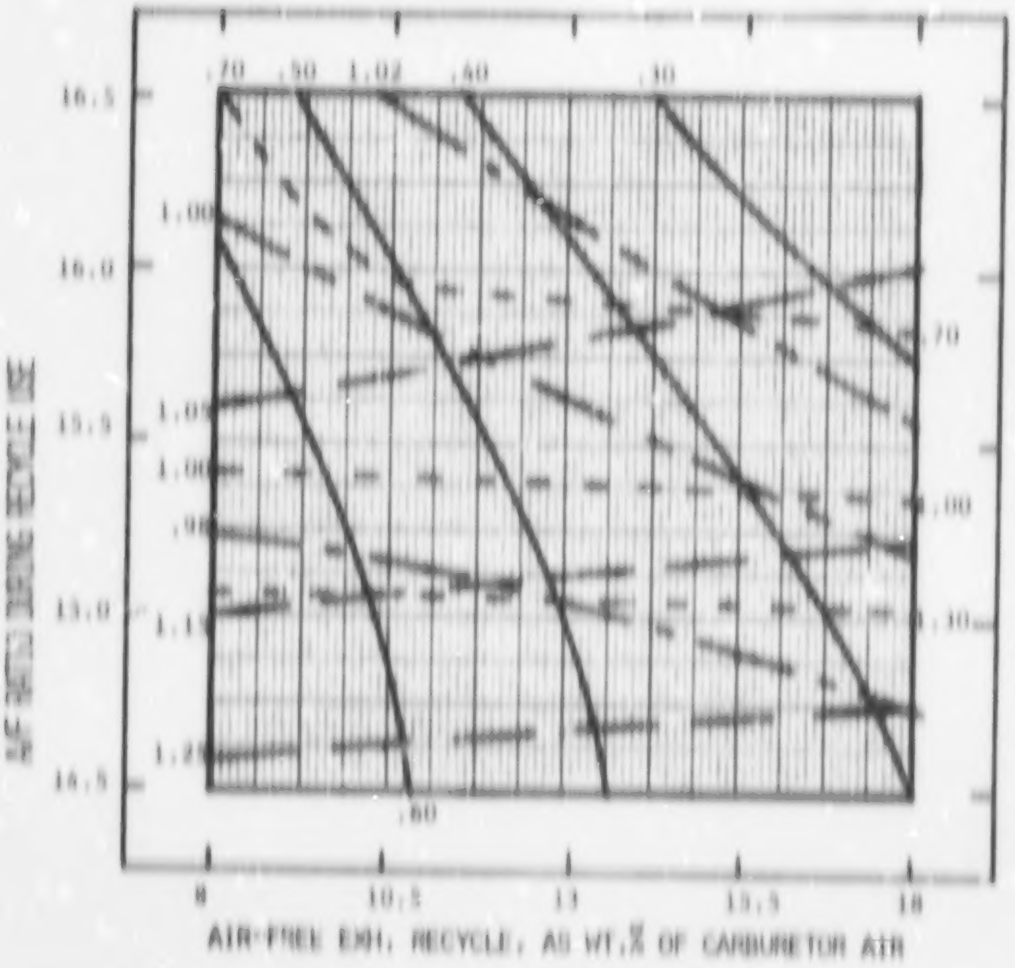
————————	NOx
—— —— ——	HC (FID)
—— - —— - ——	FUEL CONS.
- - - - - -	CO

FIGURE A2.152

USPHS EXHAUST-RECYCLE PROGRAM

PREDICTED OVERALL EFFECTS OF RECYCLE
FOR
Plymouth VEHICLE IN USPHS DRIVING CYCLE,
FOR FIXED A/F RATIO WHEN
RECYCLE IS IN USE.

SPARK CURVE ASSUMED: Mod-3



EFFECTS PLOTTED ARE RELATIVE TO BASE VEHICLE VALUES, MASS BASIS, FOR ENTIRE CYCLE.

———————— NOx
▬▬ ▬▬ ▬▬ HC (FID)
▬ - ▬ - ▬ - FUEL CONS.
- - - - - - - CO

A770

A3.0 VEHICLE TEST PHASE

A3.1 Data Compilation

The tables list the pertinent data obtained from 3/27/68 through 6/1/69. Experimental details are given in Section 3.2

A3.2 Adjustment for O_2 in Exhaust

When the exhaust contains O_2, this O_2 can be considered to be associated with 79%/21% = 3.76 times as much N_2 and, therefore, represent 4.76 times as much "air". Thus exhaust with say 4% O_2 can be said to contain 4 x 4.76% air. That part of the exhaust which is recycled will also contain such "air".

As far as the engine is concerned, this "air" is indistinguishable from the air that enters the system directly via the air cleaner and carburetor venturi. In correlating the effect of "recycle" on engine performance, it is reasonable to focus on the "inert", i.e., "air-free" recycle and to consider the "air" in the total recycle to be part of the air feeding the engine.

The algebraic relation between inert recycle and total recycle can readily be developed.

Consider unit rate of fresh air flow through the air cleaner.

Let: x = total recycle/fresh air
n = O_2 in recycle/total recycle
y = inert recycle/total air to engine.

Then: nx = O_2 in recycle/fresh air
$4.76\ nx$ = air in recycle/fresh air
$1 + 4.76\ nx$ = total air to engine/fresh air
$x - 4.76\ nx$ = inert recycle/fresh air
$y = (x - 4.76\ nx)/(1 + 4.76\ nx)$

This relation is plotted in Figure A3.10 for various O_2 levels in the exhaust.

TABLE [illegible]

[illegible]

Remarks
Unless Noted, Analyzer Calc. [illegible] Computer from Continuous Sampling, [illegible]
Hand Calc.
Bag Samples
[illegible]
[illegible]
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Bag Sample
Hand Calc. [illegible]
Hand Calc. [illegible]
Hand Calc.
Hand Calc.
Bag Sample
Bag Sample
Computer Calc.
Computer Calc.
Computer Calc.
Computer Calc.

---

* H = Hot start, C = Cold start, [illegible]

** Not measured [illegible]

TABLE A-III (Cont'd.)

SUMMARY TABLES – CALIFORNIA CYCLES –
[illegible]

[illegible]	Remarks [illegible] Computer From Continuous Sampling; [illegible] Same Batch Fuel
[illegible]	Hand Calc.
[illegible]	Hand Calc.
[illegible]	
[illegible]	Hand Calc.
[illegible]	Bag Sample of Same
[illegible]	Computer Results
[illegible]	Computer Results
[illegible]	Hand Calc.
[illegible]	Hand Calc.
[illegible]	Computer Calc.
[illegible]	Computer Calc.
[illegible]	Hand Calc.
[illegible]	Hand Calc.
[illegible]	
[illegible]	
[illegible]	
[illegible]	
[illegible]	Computer Calc.
[illegible]	Computer Calc.
[illegible]	Computer Calc.
[illegible]	Hand Calc. Same
[illegible]	Hand Calc. Same
[illegible]	Computer Calc.
[illegible]	Hand Calc.
[illegible]	Computer Calc.
[illegible]	Computer Calc.
[illegible]	
[illegible]	Hand Calc.

---

* [illegible]

** [illegible]

TABLE [illegible] (Cont'd.)

SUMMARY TABLES - CALIFORNIA CYCLE -
[illegible]

With Recycle

Without Recycle

Remarks

TABLE [illegible] (Cont'd.)

SUMMARY TABLE - CALIFORNIA CYCLE - [illegible]

With Recycle

Without Recycle

Remarks

Computer Calc.

Bag samp. of previous

Water Brake [illegible]
Initially. Bag
Sample Only

Bag sample of
previous

Bag sample of
previous

Water Brake set to
[illegible] HP max.

Water Brake set to
[illegible] HP max. Bag
sample

Water Brake set to
[illegible] HP max. Bag
sample

Water Brake set to
[illegible] HP max. Bag
sample

Water Brake set to
[illegible] HP max. Bag
sample

TABLE A-1.1 (Cont'd.)

SUMMARY TABLES – CALIFORNIA CYCLES –

[illegible]

* H = Hot start, C = Cold start, A = Computer Avg. = 0.65 H + 0.35 C.

** Not measured [illegible]

[illegible]

[illegible] – [illegible] – [illegible]

[illegible]	With Recycle	Without Recycle	Remarks
[illegible]	[illegible]	[illegible]	Bag anal. of previous
[illegible]	[illegible]	[illegible]	Bag anal. of previous
[illegible]	[illegible]	[illegible]	Bag anal. of previous
[illegible]	[illegible]	[illegible]	Bag anal. of previous cold start
[illegible]	[illegible]	[illegible]	Bag anal. of previous cold start
[illegible]	[illegible]	[illegible]	Bag anal. of previous cold start
[illegible]	[illegible]	[illegible]	Bag anal. of previous cold start
[illegible]	[illegible]	[illegible]	Power valve inoperative

* [illegible]

** [illegible]

TABLE A-11 (Cont'd.)

SUMMARY TABLES – CALIFORNIA CYCLES –

[illegible]

TABLE A-3.1 (Cont'd.)

SUMMARY TABLES - CALIFORNIA CYCLES - PLYMOUTH 413

Date (1969)	Abs. Humid. (GR) °F	Main Jet Size (in.)	Recycle: Orifice Diam. (in.)	Recycle: Total % on Air	Recycle: Insert % on Total Air	With Recycle: Start*	With Recycle: NOx (ppm)	With Recycle: CO (%)	With Recycle: HC (ppm)	With Recycle: Fuel Rate (lbs./cycle)	Without Recycle: Start*	Without Recycle: NOx (ppm)	Without Recycle: CO (%)	Without Recycle: HC (ppm)	Without Recycle: Fuel Rate (lbs./cycle)	% NOx Red'n	Remarks: Mfg. Distributor, Mfg. Jets (0.051"), Indolene Fuel, Air Flowmeter OFF Unless Noted
4/22	57	.051		0	0						C	323	2.34	347	—		Vacuum Spark Advance OFF
		(mfg.)		0	0						H	767	0.74	336	147.7		Vacuum Spark Advance OFF
				0	0						A	481	1.22	339	—		Vacuum Spark Advance OFF
				0	0						H	1393	0.84	423	135.2		Vacuum Spark Advance ON
				0	0						H	766	0.73	367	143.9		Vacuum Spark Advance OFF
4/28	44	0.051		0	0						C	2081	2.49	461	154.4		Mod-1 Distrib.
											H	1726	0.89	382	137.2		Mod-1 Distrib.
											A	1965	1.51	409	—		Mod-1 Distrib.
	43	0.051	13	13.0	—	H	774	1.44	371	136.1	H	1725	0.82	349	134.0	55	Mod-1 Distrib., Idle Screws Closed 1/2 Turn
	40	0.049	13	12.8	—	H	485	0.44	383	112.7	H	1480	0.37	432	130.6	41	Mod-1 Distrib., (Hold same idle set)
4/30	46	0.049									C	1189	1.39	436	147.3		Mod-1 Distrib.
											H	1672	0.42	382	134.0		Mod-1 Distrib.
											A	1502	0.75	400	—		Mod-1 Distrib.
	44	0.050	13	12.4	—	H	1132	0.71	372	133.4	H	1782	0.48	371	141.6	36	Mod-1 Distrib., (Larger jets)

---

* H = Hot start, C = Cold start, A = Composite Avg. = 0.65 H + 0.35 C (for California Cycles); ( ) = Estimated only.

TABLE A-3.2

SUMMARY TABLE - CALIFORNIA CYCLES IN DETROIT TESTS OF PLYMOUTH #25

Date & Test 1968	Recycle				Spark Adv.		Without Recycle			With Recycle			% NO_x Red'n.	Remarks All Tests—Warm Start All tests except 12 & 13 used 4500 lb. wts.
	Aut.	Const.	Orifice Dia. (1/32")	% on Air*	Std. 1	[illegible]	NO_x (ppm)	CO (%)	HC (ppm)	NO_x (ppm)	CO (%)	HC (ppm)		
10/28														
1					X		1440	1.39	313					
2	X		13	(12.5)	X					548	2.36	155	62	"Automatic" Recycle
3		X	13	(12.5)	X					528	2.85	417	63.4	"Automatic" Recycle
4	X		13	(12.5)	X					651	2.01	347	54.9	"Automatic" Recycle
Dow. Shift														
5	X		13	(12.5)	X					589	2.40	360	64.2	"Automatic" Recycle
6	X		14	(14.5)	X					552	2.27	349	66.4	"Automatic" Recycle
7	X		9	(7)	X					1317	0.89	320	20.0	"Automatic" Recycle
8	X		13	(12.5)	X					659	2.07	361	60.0	"Automatic" Recycle
9							1644	1.09	334					
10/31 (after carburetor rebuilt and adjusted to standard flow curve):														
Dow. Shift														
10					X		1925	0.87	333					
11	X		13	(12.5)	X					898	1.40	363	53.5	
12					[illegible]		1648	0.80	342					4000 lb. wts.
13	X		13	(12.5)	X					863	1.37	369	47.4	4000 lb. wts.

---

* Not measured if in ( ).

[illegible]

ENT

END

TABLE A-[illegible]

SUMMARY TABLE - CALIFORNIA CYCLES - [illegible]

Date	[illegible]	Main Jet Size	With Recycle	Without Recycle	Remarks
[illegible]	[illegible]	[illegible]		[illegible]	Air conditioner off
		[illegible]		[illegible]	Air conditioner off
		[illegible]		[illegible]	Air conditioner off
[illegible]	[illegible]	[illegible]		[illegible]	Air conditioner off. Idle adj. as in manual
		[illegible]		[illegible]	Air conditioner off. Air injection stopped
		[illegible]		[illegible]	Air flowmeter on
[illegible]	[illegible]	[illegible]		[illegible]	
[illegible]	[illegible]	[illegible]	Recycle Plate Installed But No Recycle Used	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Installed But No Recycle Used	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Installed But No Recycle Used	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Installed But No Recycle Used	[illegible]	Air conditioner on
		[illegible]	Recycle Plate Installed But No Recycle Used	[illegible]	Air conditioner off
[illegible]	[illegible]	[illegible]	Recycle Plate Removed	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Removed	[illegible]	Air conditioner on
		[illegible]	Recycle Plate Removed	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Removed	[illegible]	Air conditioner on
[illegible]	[illegible]	[illegible]	Recycle Plate Removed	[illegible]	Air conditioner off
		[illegible]	Recycle Plate Removed	[illegible]	Air conditioner on
[illegible]	[illegible]	[illegible]	[illegible]		Air conditioner off
		[illegible]	[illegible]		Air conditioner off
		[illegible]	[illegible]		Air conditioner off
		[illegible]	[illegible]	[illegible]	Air flowmeter on, air cond. off
		[illegible]		[illegible]	Air conditioner off
		[illegible]		[illegible]	Air conditioner off

* H = Hot Start, C = Cold Start, A = Computer Avg. [illegible] (for California Cycles); ( ) = Estimated Only

TABLE [illegible] (Cont'd.)

[illegible] - CALIFORNIA CYCLES - [illegible]

Remarks

Unless Noted, Air Conditioner is Used, Air Flowmeter Not Used, [illegible] Distributor and Spark Advance Used, Recycle Off at Full Throttle & Idle, Indolene Fuel Used

Air conditioner off
Air conditioner off
Air conditioner off
Air flowmeter on, air cond. off
Air flowmeter on
Air flowmeter on
Water cooler off
Water cooler off
Water cooler off
Water cooler off
Water cooler on, air cond. off
Water cooler on
Water cooler off
Water cooler off, air cond. off
Water cooler off
Water cooler off, air flowmeter on
Water cooler off
Water cooler off

Indolene Fuel

Water cooler off

Idle Jet Readjusted Leaner

Water cooler on

Water cooler off, air cond. off
Water cooler off, air cond. off
Water cooler off, air cond. off
Water cooler off

* H = Hot Start, C = Cold Start, [illegible] = Computed Avg. [illegible] California Cycles); [illegible] = Estimated Only

TABLE A-3.3 (Cont'd.)

SUMMARY TABLES - CALIFORNIA CYCLES - CHEVROLET V8

Date (1969)	Ave. Manif. Vacuum "	Main Jet Size #	With Recycle: Recycle Orifice Diam. # (1/64")	With Recycle: Recycle Total % of Air	With Recycle: Insert % of Total Air	With Recycle: Start*	With Recycle: NO₂ (ppm)	With Recycle: CO (%)	With Recycle: HC (ppm)	With Recycle: Fuel Rate (Gms./Cycle)	Without Recycle: Start*	Without Recycle: NO₂ (ppm)	Without Recycle: CO (%)	Without Recycle: HC (ppm)	Without Recycle: Fuel Rate (Gms./Cycle)	% NO₂ Red'n	Remarks: Unless Noted, Air Conditioner is Used, Air Flowmeter Not Used, Std. Distributor and Spark Advance Used, Recycle Off at Full Throttle Idle, Indolene Fuel Used
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Air Flowmeter On
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Continuous recycle

* H = Hot Start, C = Cold Start, A = Composite Avg. = 0.65H + 0.35C (for California Cycles); ( ) = Estimated Only

TABLE A-3.3 (Cont'd.)

SUMMARY TABLES - CALIFORNIA CYCLES - CHEVROLET (2)

Date (1966)	Abs. Humid. (Grains/#)	Tank Int. Time + 1600	Recycle: Orifice Diam. 1/32"	Recycle: Total % on Air	Recycle: Inert % in Total Air	With Recycle: Start*	With Recycle: NO_x (ppm)	With Recycle: CO (%)	With Recycle: HC (ppm)	With Recycle: Fuel Rate (Gm./Cycle)	Without Recycle: Start*	Without Recycle: NO_x (ppm)	Without Recycle: CO (%)	Without Recycle: HC (ppm)	Without Recycle: Fuel Rate (Gm./Cycle)	% NO_x Red'n.	Remarks: Unless Noted, Air Conditioner is Used, Air Cleaner Not Used, Mfg. Distributor and Spark Advance Used. Recycle Off at Full Throttle & Idle, Indolene Fuel Used
3/20	44	53	22	17.2	12.7	H	344	0.91	232	164.5	H	1285	1.32	231	167.8	53	
3/22	48	52	0	0	0						C	1303	1.59	297	—		
		52	0	0	0						H	1439	1.04	234	166.1		
		52	0	0	0						A	1405	1.23	257			
		52	13	18.4	14.0	H	388	0.80	194	160.2	H	1448	1.06	231	165.5	73.5	New square edged orifice used
3/25	57	53	13	24.2	18.4	C	187	1.75	232								New square edged [illegible] used
		53	13	24.2	18.4	H	229	1.10	163	161.7							
		53	13	24.2	18.4	A	208	1.32	186								
		53	13			H	282	1.06	194	166.7	H	1112	1.33	219	165.3	74.5	
3/26	30	53	22	14.8	13.9	H	487	0.99	183	—	H	1264	1.49	201	—	61.5	
3/30	26.5	53	0	0	0						C	771	1.75	—	—		Vac. spark adv. unused
		53	0	0	0						H	884	1.04	—	175.5		
		53	0	0	0						A	851	1.29	—	—		
		53	0	0	0						H	912	1.07	138	176.1		
		53	0	0	0						H	1365	1.10	224	182.9		Vac. spark adv. used
	27	53	22	26.8	22.9	H	362	0.93	148	185.8	H	966	1.02	227	188.9	77	Vac. spark adv. unused
4/2	62	53	22	26.8	22.7	H	395	1.00	176	173.5	H	1300	1.15	188	184.4	71	
	62	53	22	27.3	22.5	H	438	0.92	233	163.9							Spark timing advanced 5°. Engine seemed more powerful and livelier as result
		53	22	27.5	22.5	H	423	0.87	239	162.1							
4/7	24.5	53	22	25.5	21.6	C	488	1.38	324	188.4							
		53	22	25.5	21.6	H	788	1.01	236	164.7							
		53	22	25.5	21.6	A	689	1.23	276	—							
4/26	78	53	20	23.5	20.0	C	380	0.94	243	198.4							
		53	20	23.5	20.2	H	443	0.53	228	167.5							
		53	20	23.5	20.1	A	332	0.66	227	—							
		55	20	23.6	20.4	H	496	0.52	225	162.2	H	1243	0.84	230	162.3	64	Recycle reached on inside meter
[illegible]	106	53	23	21.2	16.1	C	234	1.09+	292+	—							Idle = 2.5% CO
				21.5	16.3	H	227	1.11	227	171.8							
						A	229	1.10+	264+								
				20.6	15.5	H	326	0.57	217	178.3	H	1194	1.16	249	163.8	73	Idle reset to 1.5% CO
5/3	40	53									C	1313	1.47	257			
											H	1384	0.74	221	169.2		
											A	1365	1.00	226			
			22	29.2	24.4	H	422	0.47	229	166.0	H	1421	0.84	222	164.1	56.5	

---

* H = Hot start, C = Cold start, A = Computer Avg. = 0.65 H + 0.35 C (for California Cycles); ( ) = Estimated only.

TABLE A-1.1 (Cont'd.)

SUMMARY TABLES - CALIFORNIA CYCLES - CHEVROLET [illegible]

			With Recycle								Without Recycle						Remarks
			Recycle														
Date (1969)	Abs. Humid. (Grains / #)	Main Jet Size x .001"	Orifice Diam. x 1/32"	Total % on Air	Inert % on Total Air	Start*	NO_x (ppm)	CO (%)	HC (ppm)	Fuel Rate (Gms. / Cycle)	Start*	NO_x (ppm)	CO (%)	HC (ppm)	Fuel Rate (Gms. / Cycle)	% NO_x Red'n.	Unless Noted, Air Conditioner in Used, Air Flowmeter Not Used, 45# Distributor and Spark Advance Used, Recycle Off at Full Throttle & Idle, Indolene Fuel Used
3/20	36	47	14	23.5	18.0	C	257	1.71	247								
		—	14	24.3	18.4	H	230	1.01	186	188.9							
		51	14			A	285	1.25	224								
		51	14	22.7	16.2	H	372	0.80	201	181.3	H	1511	1.23	251	188.4	75	Car surged with recycle
3/5	15	54	28	25.85	19.0	H	186	1.70	183	167.7	H	1124	1.61	214	201.3	83.5	
3/6	14	53	28	25.1	19.1	C	148	2.95	249	—							
		53	28			H	185	2.30	196	210.9							
		53	28			A	158	2.64	224								
		53	14	26.7	20.3	H	222	1.89	179	214.6	H	1287	1.42	197	168.8	83	
3/7	22	53	14	23.0	17.0	H	260	1.05	187	172.1	H	1309	1.31	210	161.5	80	Less Extra Fuel
	23	53	14	22.9	17.4	H	285	1.15	163	186.0	H	1330	1.29	207	164.8	79	
	23	53	14	23.3	17.6	C	282	2.75	251	—							
		53	14			H	227	1.38	171	196.9							
		53	14			A	211	1.90	198								
3/10	23.5	53	14	23.4	(17.5)	C	228	1.44	231	—							Car turns off power valve spring
		53	14	22.7	16.7	H	258	1.16	194	—							Same
		53	14			A	243	1.51	228	—							Same
		53	14	23.2	17.0	H	181	1.12	173	—	H	1323	1.36	217	—	79	Same
		53	12	16.8	12.4	H	388	0.90	217	—	H	1365	1.35	229	—	54	Same
3/11	25	53	14	24.25	17.9	C	[illegible]	1.53	243	—							
		53	14	24.6	17.8	H	267	0.84	181	180.9							Fine total turns off power valve
		51	14			A	229	1.14	203	192.6							setting-used hereafter
		53	14	23.6	17.5	H	221	0.95	185	—	H	1371	1.25	224	194.3	84	
3/12	17	53	13	19.85	15.0	C	308	1.05	207	—							
		53	13	19.8	14.1	H	382	0.82	173	182.4							
		53	13			A	342	0.89	184								
		53	13	19.1	14.0	H	430	0.82	204	173.7	H	1389	1.39	235	180.0	67	
3/17	23.5	53	13	19.1	14.6	H	470	0.86	217	176.5	H	1346	1.33	223	188.5	64	
3/20	42	53	0	0	0						C	1285	1.36	242			
		53	0	0	0						H	1227	1.36	253	171.0		
		53	0	0	0						A	1229	1.42	224			
		53	15			H	289	0.93	262	185.3	H	1249	1.37	202	186.9	77	

* H = Hot Start, C = Cold Start, A = Computed avg. = 0.65H + 0.35C (for California Cycles); ( ) = Estimated Only

TABLE A-13

[illegible] TABLES - [illegible] CYCLES - CHEVROLET V8

Date (1966)	Ave. Manif. Vacuum	Valve Jet Size ×.001	Recycle Orifice Diam. × 1/32"	Recycle Total % on Air	Recycle Inert % on Total Air	With Recycle Start*	With Recycle NOx (ppm)	With Recycle CO (%)	With Recycle HC (ppm)	With Recycle Fuel Rate (gm/cycle)	Without Recycle Start*	Without Recycle NOx (ppm)	Without Recycle CO (%)	Without Recycle HC (ppm)	Without Recycle Fuel Rate (gm/cycle)	% NOx Red'n	Remarks (All Gas Samples from Bags of Total Exhaust)
3/27	23.3	50	10	24.5	17.2	H	132	2.77	184	224.4	H	452	2.13	270	174.8	79	
3/28	17	50	—	0	0						C	560	2.37	285	200.2		All runs made with air conditioner ON, air cleaner OFF, manufacturer's distributor and spark setting, Indolene fuel
	17	50	—	0	0						H	465	2.23	260	178.8		
	26	50	20	27.1	12.4	H	222	2.0	285	251.8	H	422	2.22	288	214.8	40	
	20	50	16	29.5	7.3	H	305	1.42	288	282.1	H	427	2.01	288	272.3	32	
	14	50	11	24.8	11.2	H	380	1.93	282	294.8	H	730	2.02	288	274.7	75	

---

* H = Hot Start, C = Cold Start

TABLE A-3.7

SUMMARY TABLES - STEADY STATE RUNS - CHEVROLET 409

					With Recycle									Without Recycle							
								Recycle													
Date (1969)	Abs. Humid. (Grains/lb)	Speed MPH or RPM	H.P.	Main Jet Size x .001	Venturi Air Flow CFM	Fuel Rate #/Min.	Air Fuel A/F	Orifice Diam. x 1/32"	Total Inert % on Air	% on Total Air	NO_x (ppm)	CO (%)	HC (ppm)	Venturi Air Flow CFM	Fuel Rate #/Min.	Air Fuel A/F	NO_x (ppm)	CO (%)	HC (ppm)	% NO_x Red'n	Remarks Indolene Fuel Unless Noted-Air Inst. and Water Cooler on Unless Noted
1/28	17	20	Unloaded	53		—	—	12	17.9	12.7	180	0.75	101		—	—	170	0.49	75	42	Ponca Extra Fuel, Air Conditioner Off Air Flowmeter On
		30		53		—	—	12	16.5	10.1	170	0.53	128		—	—	450	0.53	122	62	
		40		53		—	—	12	18.6	11.3	220	0.41	109		—	—	720	0.53	98	69.5	
		50		53		—	—	12	18.5	11.8	290	0.45	84		—	—	1080	0.45	84	73	
1/29	16	20		53	20.0	—	—	12	—	—	140	0.78	153	20.5	—	—	357	0.38	125	61	Ponca Extra Fuel Air Conditioner On Air Flowmeter On
		30		53	30.0	—	—	12	16.6	10.2	170	0.28	142	28.5	—	—	860	0.42	137	80	
		40		53	41.0	—	—	12	17.8	11.5	335	0.35	112	40.2	—	—	1270	0.36	110	73.5	
		50		53	50.2	—	—	12	17.1	11.4	400	0.30	96	51.0	—	—	1275	0.33	89	68.5	
		1500	20	53	—	—	—	12	—	—	—	—	—	42.5	0.221	24.42	1670	0.47	158	84	
		1500	20	53	42.5	0.202	16.7	12	20.2	13.3	680	0.38	162	—	—	—	—	—	—		
		1500	42	53	—	—	—	12	—	—	—	—	—	53.3	0.2764	24.45	2285	0.67	177	59	
		1500	39	53	51.5	0.2703	14.9	12	18.6	13.1	695	0.30	170	—	—	—	—	—	—		
		1500	56	53	—	—	—	12	—	—	—	—	—	38.5	0.386	24.25	2320	0.95	174	62.5	
		1500	38.5	53	59.2	0.296	15.55	12	18.2	13.9	860	0.71	150	—	—	—	—	—	—		
		2000	60	53	—	—	—	12	—	—	—	—	—	64.3	0.417	15.2	2380	1.02	107	65	Actually 1/32 Inert Recycle Due to Valve Leakage at High Load
		2000	74	53	65.0	0.435	16.7	12	16.7	11.6	925	0.78	96	—	—	—	—	—	—		
2/4	13	20	Unloaded	53										—	—	—	450	0.52	142		Air Flowmeter Off
		30		53										—	—	—	980	0.57	142		
		40		53										—	—	—	1180	0.56	117		
		50		53										—	—	—	1370	0.54	95		
		50		53										51.7	—	—	1420	0.64	84		Air Flowmeter On
		40		53										40.7	—	—	1285	0.60	109		
		30		53										29.2	—	—	940	0.62	131		
		20		53										21.0	—	—	330	0.51	111		

TABLE A-3.7 (Cont'd.)

SUMMARY TABLES - STEADY STATE RUNS - CHEVROLET #2

					With Recycle									Without Recycle							
								Recycle													
Date (1969)	Abs. Humid. (Grains/#)	Speed MPH or RPM	H.P.	Main Jet Size x .001"	Venturi Air Flow CFM	Fuel Rate #/Min.	Air Fuel A/F	Orifice Diam. x 1/32"	Total % on Air	Inert % on Total Air	NO$_x$ (ppm)	CO (%)	HC (ppm)	Venturi Air Flow CFM	Fuel Rate #/Min.	Air Fuel A/F	NO$_x$ (ppm)	CO (%)	HC (ppm)	% NO$_x$ Red'n	Remarks (As Before)
2/5	17	Idle	Unloaded	53	22.6	—	—	12	—	—	60	2.75	238	22.6	—	—	140	1.53	286	57	Air Flowmeter In During Run
		20		53	20.4	0.1118	14.32	12	16.3	10.9	140	0.97	168	21.5	0.1094	15.23	410	0.58	144	66	
		30		53	31.7	0.1480	16.00	12	18.7	11.7	290	0.75	136	30.4	0.1464	15.67	955	1.38	136	70	
		40		53	40.0	0.2014	15.29	12	17.6	11.6	370	0.50	94	40.8	0.2023	15.23	2045	0.65	88	84.5	
		50		57	51.0	0.256	15.57	12	15.5	10.6	435	0.67	73	51.0	0.2606	14.97	2200	1.75	61	84	
		50		53	51.6	0.2584	15.57	12	15.8	10.7	460	0.67	70	52.0	0.2488	15.31	2385	0.67	61	81	
		60		53	67.0	0.330	15.77	12	14.5	10.4	520	0.79	50	66.3	0.3233	15.87	2400	0.85	41	80	
2/6	26	Idle		53	—	—		12	—	—	130	1.38	198	—	—		390	0.67	232	33	Air Flowmeter Out
		20		53	—	—		12	—	—	225	0.97	180	—	—		520	0.57	186	60	
		30		53	—	—		12	(24.2)	(8.6)	385	0.42	156	—	—		1015	0.61	162	62	
		40		53	—	—		12	(28.3)	(11.3)	460	0.57	144	—	—		2385	0.79	138	81	
		50		53	—	—		12	(27.3)	(11.2)	500	0.75	113	—	—		2275	0.97	108	78	
2/7	15	50	—	58	53.7	0.2793	15.01	12	16.1	10.8	420	0.65	100	53.2	0.267	14.94	2440	0.61	91	71	Air Flowmeter In
		51	3-5	53	56.6	0.2838	15.63	12	15.2	10.4	520	0.70	108	53.5	0.2624	15.29	2211	0.65	91	57	
		50	4-5	53	—	—	—	12	—	—	—	—	—	53.0	0.262	15.17	2221	0.65	91	—	
		62	3-7	73	78.5	[illegible]	15.06	12	14.0	10.2	480	0.90	86	66.5	0.3309	15.05	2372	0.67	70	56	
		40	6-7	53	42.5	(0.2222)	(15.73)	12	16.2	10.6	470	0.59	137	45.0	(0.2222)	(15.90)	2238	0.61	227	62	
		30	7-10	53	39.8	0.1765	16.82	12	18.0	12.4	570	0.38	166	38.5	0.1842	15.69	1365	0.52	171	59	
2/11	23	Idle		52	—	—		12	—	—	—	—	—	—	—		205	0.90	290	—	Air Flowmeter Out
		20		52	—	—		12	(29.7)	(12.3)	155	0.94	180	—	—		410	0.42	138	62	
		30		52	—	—		12	(28.2)	(11.8)	335	0.35	161	—	—		821	0.47	161	59	
		40		52	—	—		12	(28.4)	(11.8)	410	0.42	142	—	—		1115	0.57	144	63	
		50		52	—	—		12	(27.2)	(11.5)	430	0.61	161	—	—		2150	0.75	98	81	
2/13	21	Idle	Unloaded	54	—	—		12	—	—	100	2.38	208	—	—		220	0.93	245	—	Air Flowmeter Out
		20		54	—	—		12	(28.6)	(12.0)	170	0.97	183	—	—		425	0.57	186	61	
		30		54	—	—		12	(24.9)	(9.4)	360	0.47	156	—	—		940	0.65	186	62	
		40		54	—	—		12	(28.0)	(11.6)	420	0.61	149	—	—		940	0.97	134	55	
		50		56	—	—		12	(26.6)	(11.1)	425	0.94	111	—	—		985	1.25	88	56	
2/14	17	Idle		53	—	—		12	—	—	60	2.22	255	—	—		380	0.90	286	—	Air Flowmeter In
		20		53	20	—		12	—	—	140	0.90	180	20.5	—		400	0.47	156	65	
		30		53	31	—		12	—	—	385	0.32	161	29.5	—		970	0.42	162	60.5	
		40		53	39.5	—		12	19.0	12.3	360	0.38	142	39	—		1295	0.50	136	72	
		50		53	50.3	—		12	17.7	12.7	410	0.61	113	50.5	—		2470	0.57	108	73	
		60		53	64.0	—		12	15.9	11.3	460	0.70	94	61.5	—		2325	0.75	77	80	

( ) - Estimated only, not measured.

TABLE A-2.7 (Cont'd.)

SUMMARY TABLES - STEADY STATE RUNS - CHEVROLET V8

Date (1966)	Abs. Humid. (Grains) °F	Speed RPM or MPH	H.P.	Main Jet Size x .001"	With Recycle: Venturi Air Flow CFM	Fuel Rate #/Min.	Air-Fuel A/F	Recycle: Orifice Diam. x 1/32"	Total % on Air	Inert % on Total Air	NO$_x$ (ppm)	CO (%)	HC (ppm)	Without Recycle: Venturi Air Flow CFM	Fuel Rate #/Min.	Air-Fuel A/F	NO$_x$ (ppm)	CO (%)	HC (ppm)	% NO$_x$ Red'n	Remarks As Before, Air Flowmeter (CC) While Test Measured Unless Noted
2/17	25	Idle	Unloaded	53				22			140	0.90	176				390	0.75	171	—	
		20		53				20			251	0.79	148				435	0.90	296	40.5	
		30		53				20			500	0.35	151				970	0.57	296	48.5	
		40		53				20			570	0.30	139				1060	0.72	132	47	
		50		53				20			585	0.78	106				1130	0.93	100	48	
		60		53				11			735	0.99	86				1330	1.02	70	45	
2/17	25	Idle	Unloaded	52				20			300	0.75	193				235	0.34	190	—	
		20		52				20			190	0.57	183				450	0.38	173	58	
		30		52				20			425	0.32	159				865	0.42	162	50	
		40		52				20			520	0.42	142				1150	0.57	110	55	
		50		52				20	(13.2)		550	0.42	109				1150	0.75	100	52	
		60		52				20	(11.7)		675	0.75	41				1395	0.80	74	51	
2/18	29	Idle	0	52	—	—	—	20	—	—	185	1.15	212	—	—	—	255	0.35	202	—	
		1000	5	52	—	0.1335	—	20	—	—	430	0.58	186	—	0.1122	—	950	0.57	244	55	
		1500	7-7.5	52	37.4	0.1887	15.45	20	13.9	10.7	770	0.35	162	38.4	0.2977	14.53	1240	0.42	161	38	
		2000	10	52	51.0	0.267	14.79	20	12.9	9.2	770	0.43	122	50	0.2639	14.22	1450	0.42	120	47	
		2500	12.5	52	70.6	0.3554	15.28	20	11.7	8.9	865	0.79	91	70	0.332	14.91	1675	0.70	94	48.5	
		2500	14	52	78.9	0.3857	15.47	20	11.3	8.9	1125	0.90	100	78	0.394	14.86	2000	0.87	86	44	
		2000	20	52	77.4	0.3804	15.52	20	12.3	8.9	1075	1.76	136	63	0.321	14.22	2020	0.82	134	47	
		50	0	52	48.3	0.2606	14.66	20	17.3	9.0	540	0.33	91	51	0.266	14.38	1280	0.60	94	57.5	
		60	0	52	62.3	0.3275	14.71	20	12.5	8.5	630	0.65	70	63	0.312	14.33	1355	0.65	94	53.5	
2/19	34	Idle	Unloaded	53	—	—		20	—	—	220	0.75	183	—			220	0.57	178	—	
		20		53	—	0.1221		20	—	—	265	0.65	166	—	0.101		500	0.47	152	47	
		30		53	29.1	0.240	16.42	20	13.3	8.1	340	0.32	152	27.5	0.1403	14.70	795	0.50	148	57	
		40.4		53	35.6	0.186	15.10	20	16.4	10.4	435	0.47	132	35.0			1050	0.67	127	58	
		50		53	43.5	0.242	14.02	20	14.1	9.6	465	0.75	92		0.248		965	0.90	92	48	
		60		57	58.0	0.303	14.79	20	12.4	8.9	540	0.76	70	37.5	0.311	13.67	1080	0.92	66	48	

( ) = Estimated only, not measured.

TABLE A-1.7 (Cont'd.)

SUMMARY TABLES - STEADY STATE RUNS - [illegible]

( ) - Estimated only, not measured.

TABLE A-3.9

DRIVEABILITY TESTS - PLYMOUTH #3 WITH MOD.-1 DISTRIBUTOR

Date	Continuous Recycle Orifice Size	Continuous Recycle % on Air	Test Conditions	Results	Average Acceleration Time (Secs.) 0-60 mph	Average Acceleration Time (Secs.) [illegible] mph
4/15/60	—	0	Dec. Spark advance 10°-cold Mfg. Distribution Instead of Mod - 1. [illegible]	Generally satisfactory (light idle roughness, no light P.T. hesitation)		
	—	0	Normal exc. Mfg. Dist.	Same—all items satisfactory but no light stumble and idling roughness	11.82	15.30
3/24/60	13/32"	12.5	Normal	—		
3/2/60	15/32"	17	Cold start @ 27°F Normal set up	Satisfactory accel. and idle	11.76	15.22
12/24/60	0	0	Cold start @ 32°F	Rough idle at start—light to heavy hesitation and stumble at WOT for first mile—part-throttle accel. satisfactory		
	15/32"	17	After 1/4 mile	Moderate to heavy hesitation and stumble at WOT for 1/4 mile. Part throttle and idle satisfactory Accel. (WOT or part throttle) shows moderate hesitation and stumble. Satisfactory after 3/4 mile		
12/30/60	15/32"	17	Cold start @ 40°F	Part throttle and idle—satisfactory WOT—heavy stumbling		
	0	0	Power valve opening at lower vac. After 0.1 mile	Idle rough—stalled on part-throttle acceleration. Light to heavy hesitation on WOT and part-throttle accels.		
	15/32"	17	After 0.7 mile	Moderate hesitation on WOT accel. Part throttle satisfactory. Everything satisfactory after 1.7 miles		
12/13/60	0	0	Cold start @ 42°F Power valve as set by Chrysler	Idle rough—part throttle accel. satisfactory		
	15/32"	17	After 0.1 mile	Trace to moderate hesitation and stumble on WOT and part throttle accel.		
	0	0	After 0.3 mile	Part-throttle accel. satisfactory. WOT accel—light hesitation, even stalling		
	15/32"	17	After 0.7 mile	Occasional hesitation on accel. but generally satisfactory		
12/22/60	0	0	Cold start at 42°F	Idle rough, occasional hesitation on WOT accel. Generally satisfactory otherwise.		
	13/32"	12.5	After 0.7 mile	Part-throttle accel. satisfactory; WOT accel—light to moderate hesitation		
	0	0	After 1.2 mile	Satisfactory except for light hesitation on WOT accel.		

TABLE A-1.8 (Cont'd.)

Date	Continuous Recycle Orifice Size	% on Air	Test Conditions	Results	Average Acceleration Time (Secs.) 0-30 MPH	0-60 MPH	0-70 MPH
12/11/48	0	0	Normal except second stage of power valve never opens Cold start at 23°F	Idle rough—light to heavy hesitation and stalls on WOT accel. for 1.8 miles Part-throttle accel. satisfactory			
12/20/48	13/32"	12.5	Same as 12/11/48	Initially part-throttle accel.—satisfactory, WOT accel.—heavy hesitation and stumble			
			After 0.1 mile	Repeated stalling on all accels. and idle			
	0	0	After 1.5 mile	Part-throttle OK, WOT—moderate stumble + hesitation			
9/13/49	13/32"	12.5	Normal	Cruise tests—OK, accels. (both WOT and part-throttle)—trace to moderate surge & hesitation. PT crowd (20-70)—OK			Before Soak = 19.7 After Soak = 19.4
9/13/49	11/32"	9.5	Normal	PT crowd & tip-in—OK, trace hesitation & surge on WOT and PT accels.			Before Soak = 17.2 After Soak = 17.7
9/13/49	13/32"	12.5	Cold start @ 73°F (Engine about 90°F)	Idle moderately rough, even when warm. Initial accels. (WOT & PT)—trace of hesitation—otherwise all satisfactory			
9/13/49	11/32"	9.5	Cold start @ 73°F (Engine about 65°F)	Idle slightly rough, otherwise all accels. (WOT & PT) satisfactory			
9/22/49	0	0	Normal	Trace of surge on rapid accels., otherwise all tests satisfactory			Before Soak = 18.7 After Soak = 11.3
9/22/49	0	0	Cold start @ 73°F (Engine about 65°F)	A few slight stumbles in first few part-throttle accels., then all satisfactory			
9/23/49	0	0	Normal	All tests satisfactory			
	9/32"	7+	Normal	Generally satisfactory, trace of hesitation on a few PT accels.			
	11/32"	9.5	Normal	Generally satisfactory—WOT accel.—trace surge, PT accel.—trace to moderate hesitation and surge			
	13/32"	12.5	Normal	Cruise, PT crowd, PT tip-in tests—OK WOT and PT accels.—trace to moderate hesitation, surge & stretchiness About limit for acceptable driving			
9/23/49	0	0	Normal	Trace surge on some accels. Otherwise OK		9.40	12.60
	9/32"	7+	Normal	Trace surge on some accels. Otherwise OK		10.60	13.40
	11/32"	9.5	Normal	Trace to moderate surge on some accels. Otherwise OK		10.30	14.20
	13/32"	12.5	Normal	Moderate hesitation & surge on PT accels. Trace to moderate hesitation & surge on WOT accels. Otherwise satisfactory		10.80	15.10

3042-

[illegible]

[illegible]

Date	Continuous [illegible]			Test Conditions	Results	Average Acceleration Time (Secs.)					
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE A-13 (Cont'd.)

Date	Continuous Recycle* Orifice Size	% [illegible] Total	% [illegible] Inert	Test Conditions	Results	Average Acceleration Time (Secs.) With Recycle 0-30 mph	With Recycle 0-40 mph	With Recycle 0-70 mph	Without Recycle** 0-30 mph	Without Recycle** 0-40 mph	Without Recycle** 0-70 mph
[illegible]	[illegible]	[illegible]	[illegible]	Normal (0.025" gap)	Generally satisfactory - trace of surge at high cruise speeds and trace of hesitation on WOT accels.-probably acceptable.			[illegible]			[illegible]
	[illegible]	[illegible]	[illegible]	Normal (0.025" gap)	Satisfactory on all tests			[illegible]			[illegible]
	[illegible]	[illegible]	[illegible]	Normal (0.025" gap)-cold (20°F) start	Trace hesitation and stumble on accel. for first 1/4 mile. Then everything satisfactory						
[illegible]	0	0*	0*	Cold start at 20°F Normal setup (.025" gap)	Moderate to heavy "hesitation" and stumble with repeated stalls & backfire when accelerator floored during first 1/4 mile. Part-throttle satisfactory. After 1/4 mile, even WOT satisfactory.						

---

* At speeds above 50 mph with wide-open throttle, muffler back pressure was so high that it pushed the closed recycle valve partially open, thus causing a few percent recycle near the end of each acceleration.

** Engine roughness, especially after Powerglide shifted gears @ 35 mph.

FIGURE A3.10

ADJUSTMENT OF RECYCLE MEASUREMENTS FOR AIR IN EXHAUST